

# Ex Ante Assessment of the Distributional Effects of Urban Policies

*Évaluation ex ante des effets redistributifs  
de politiques urbaines*

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**Titre :** Evaluation ex ante des effets redistributifs de politiques urbaines

**Mots clés :** Economie urbaine, Inégalités, Transport, Logement, Usage des sols

**Résumé :** La concentration de la population et des emplois dans des villes de plus en plus importantes génère des bénéfices d'agglomération, mais aussi des coûts, en particulier des dépenses de logement élevées et de longs déplacements pendulaires, qui peuvent peser lourdement sur les ménages à faibles revenus. Les politiques urbaines peuvent atténuer ces coûts, mais leurs effets redistributifs dépendent de la manière dont les ménages se localisent dans les zones urbaines en fonction de leurs revenus. Après une revue de la littérature sur les mécanismes guidant la répartition spatiale des ménages, nous développons un nouveau mécanisme théorique, reposant sur le modèle canonique de l'économie urbaine dans lequel nous introduisons une demande inélastique pour le logement. Le modèle reproduit des observations empiriques sur la structure des villes américaines, et sur les dépenses en logement de leurs habitants.

Le deuxième article étudie l'effet des nouvelles infrastructures de transport, en dérivant un modèle d'équilibre partiel qui s'appuie sur des mesures d'accessibilité spécifiques à chaque groupe d'habitants. Le modèle est utilisé pour anticiper les effets de futures lignes de métro dans la région parisienne, avec des paramètres calibrés à l'aide de données historiques sur la localisation des ménages.

Le dernier chapitre présente l'architecture d'un modèle Transport-Usage des sols appliqué à ville du Cap, en Afrique du Sud, s'appuyant sur des mécanismes discutés précédemment et en incluant une représentation explicite de l'habitat informel. Ce modèle peut être utilisé pour simuler les effets de politiques d'aménagement du territoire et de transport, en mettant en évidence des arbitrages ou synergies potentiels entre les objectifs d'efficacité et d'équité.

**Title:** Ex Ante Assessment of the Distributional Effects of Urban Policies

**Keywords:** Urban Economics, Inequality, Transport, Housing, Land Use

**Abstract:** The spatial clustering of residents and businesses in ever larger urban areas leads to agglomeration benefits but also to costs, in particular high housing costs and long commutes, that can weigh heavily on low-income households. Urban policies can alleviate these costs, but their effects depends on how households locate themselves in urban areas depending on their income ("income sorting"). After a literature review on the mechanisms driving income sorting, we develop a new mechanism of income sorting, based on the canonical model of urban economics in which we introduce an inelastic demand for housing. The model predictions are consistent with empirical features of inner-city gentrification in large US cities, as well as housing spendings of their residents.

The third chapter focuses on the effect of new transit infrastructure on income sorting, by deriving a simple partial equilibrium model that relies on group-specific accessibility measures. The model is used to anticipate the effects of a future metro line in the Paris region, with parameters calibrated using historical data on household location.

The final chapter presents the architecture of a land-use and transport interaction model applied to Cape Town, South Africa, based on the mechanisms discussed in the previous chapters. The model also includes an explicit representation of informal housing. This model can be used to simulate the impacts land use and transport policies, and highlight potential trade-offs or synergies between efficiency and equity objectives.

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# Long Abstract

This dissertation aims at providing tools to anticipate the distributional effects of transport and planning policies at the metropolitan scale. Such policies become increasingly important due to the rapid growth of cities. The spatial clustering of residents and businesses in ever larger urban areas leads to agglomeration benefits but also to costs, in particular high housing costs and long commutes. In a context of growing local inequalities, these costs seem to weigh heavily on low-income households. The distribution of housing and transport costs along income depends critically on how households locate themselves in urban areas depending on their income (“income sorting”). In order to anticipate the impacts of urban policies over the long term, it is crucial to understand how such policies alter income sorting. The first part of this dissertation focuses on this question (chapters 2 and 3). Then, chapters 4 and 5 aim at building models for the *ex ante* assessment of urban policies, with an explicit modeling of income sorting.

Chapter 2 reviews the main theories of income sorting within cities provided by urban economics. Some stylized facts show that spatial patterns vary widely across cities, and that neighborhoods change differently across time. As a consequence, urban economics does not provide a unique theory of income sorting, but a multitude of mechanisms. The choice of which mechanisms to include in a prospective model depends primarily on what policy will be simulated.

In chapter 3, we develop a new mechanism of income sorting, motivated by the recent trend of inner-city gentrification in large metropolitan areas in North America and in Europe. The causes of the increase in relative socioeconomic status of central areas of cities are yet to be completely understood. In chapter 3, we show that the canonical model of urban economics can reproduce the observed features of gentrification when we introduce an inelastic demand for housing. We derive a monocentric model of a city where inhabitants are divided in two income groups, and where demand follows a Stone-Geary utility function. The model predictions are consistent with empirical features of inner-city gentrification in large US cities. In line with the theory, we also show that housing spendings depend on city size, land use constraints, as well as local income distribution.

Chapter 4 focuses on the effect of new transit infrastructure on income sorting. In the economic literature, public transit is generally seen as a pro-poor policy, but new transit infrastructure are criticized when they foster gentrification in served locations. The existing empirical literature does not enable to conclude on a systematic effect of

## Abstract

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new transit lines. Here, we argue that improvement in transit infrastructure does not increase accessibility uniformly across groups of residents, as jobs occupied by workers of different occupational categories are not equally distributed in space. This in turn alters the composition of neighborhoods. We formalize this intuition using group-specific gravity measures of accessibility to jobs, that we embed in a partial equilibrium model of the housing market. We test our model using the changes in the rail transit network in the Paris region between 1968 and 2015, and estimate the key parameters. This work rationalizes why previous empirical works find heterogeneous results depending on the transit line studied. We then anticipate the effects of the Grand Paris Express (GPE), a transport project under construction. We simulate that the GPE will lead to gentrification in a majority of the municipalities served, but we estimate that, overall, the project will have a positive distributional effect. We conclude that public transit can be a pro-poor policy even if it induces gentrification.

Chapter 5 presents the architecture of a Land-Use and Transport Interaction (LUTI) model applied to Cape Town, South Africa. The model is based on the mechanisms discussed in chapters 3 and 4. It also includes an explicit representation of informal housing. Households may choose to live in informal housing as the result of a trade-off between accessibility, housing affordability and comfort. We structurally estimate the main parameters, using local census and administrative data. The model illustrates how planning policies may have unintended consequences on the number of informal dwellers. As an example, we simulate the potential effects of an Urban Growth Boundary policy in a reference scenario, and find that it may significantly increase the number of informal dwellings by 2040. This model can be used to simulate multiple land use and transport policies, and highlight potential trade-offs or synergies between efficiency and equity objectives.

# Résumé long

## Introduction

L'objectif de cette thèse est de fournir des outils pour anticiper les effets redistributifs des politiques de transport et d'aménagement urbain. Le regroupement des ménages et des entreprises dans des zones urbaines de plus en plus peuplées et étendues entraîne des bénéfices d'agglomération mais aussi des coûts, en particulier des coûts de logement élevés et de longs trajets domicile-travail. Dans un contexte de croissance des inégalités aux échelles nationales et locales, ces coûts semblent peser de manière disproportionnée sur les ménages à bas revenus.

Des politiques d'aménagement, de logement et de transports à l'échelle des agglomérations permettent d'accompagner l'urbanisation et de limiter les coûts associés. Leur mise en œuvre doit cependant prendre en compte le caractère systémique des interactions entre accessibilité, marchés immobiliers et fonciers et usage des sols, ainsi que l'inertie des infrastructures qui composent les villes. Il est alors nécessaire d'évaluer en amont les effets de ces politiques. Prendre en compte les effets hétérogènes selon les revenus permet de concevoir des politiques redistributives, donc plus acceptables, et peut également permettre une meilleure représentation des systèmes urbains, en particulier dans les villes très inégalitaires.

Des modèles de simulation sont utiles pour faire des analyses prospectives afin d'éclairer la décision publique, en particulier des modèles reposant sur le formalisme de l'économie urbaine, utilisé dans cette thèse. Intégrer l'hétérogénéité des ménages dans de tels modèles reste un défi, car cela nécessite une représentation de la façon dont des ménages avec des revenus différents se répartissent dans l'espace urbain (*income sorting* en anglais). Il est alors nécessaire de comprendre les mécanismes de répartition spatiale selon le revenu. La première partie de cette thèse se concentre sur cette question tandis que la deuxième vise à construire des modèles pour l'évaluation prospective des effets de politiques urbaines.

## Première partie : la répartition spatiale des ménages selon le revenu en ville

Le **chapitre 2** propose une revue de la littérature en économie urbaine traitant de la répartition intra-métropolitaine des habitants selon leur revenu. Cette répartition peut

générer des inégalités de deux types : celles liées à la composition des quartiers et à la ségrégation (“effets de voisinage”) et les inégalités d’accès à certaines ressources non uniformément réparties (emplois, aménités, services publics, etc.).

Les principaux faits stylisés montrent que les structures spatiales varient largement d’une ville à l’autre, et que ces structures évoluent au cours du temps, parfois rapidement. Face à la diversité des situations empiriques, la littérature en économie urbaine ne propose pas une théorie unique, standard, de la répartition spatiale des revenus, mais met plutôt en avant une multitude de mécanismes à l’œuvre. Les principaux sont (i) l’arbitrage entre transport et coûts du logement, (ii) les effets de voisinage, (iii) les aménités locales et (iv) les mécanismes reposant sur la qualité ou le type de logements (notamment habitat formel/informel). Le choix des mécanismes à inclure dans un modèle prospectif dépend principalement du degré de complexité recherché, et du type de politique publique dont on souhaite évaluer les effets.

Dans le **chapitre 3**, on contribue à cette littérature en proposant un modèle théorique reposant sur “l’abordabilité” du logement. Dans les grandes métropoles nord-américaines et européennes, au cours de ces dernières décennies, les centres-villes ont connu un phénomène de *gentrification*, c’est-à-dire une augmentation relative de leur statut socioéconomique. Plusieurs facteurs peuvent expliquer ce phénomène, mais la littérature économique a peu mis en avant la question du coût croissant des logements. Le mécanisme théorique présenté ici repose sur le modèle canonique de l’économie urbaine, qui présuppose que les ménages font un arbitrage entre coût des transports et coût du logement. On introduit dans ce modèle une fonction d’utilité de Stone-Geary, où les ménages doivent avoir une consommation minimale de logement. Cette représentation traduit le fait que le logement est un bien de première nécessité. On montre théoriquement que deux structures de ville sont possibles : une structure *centre pauvre - périphérie riche*, et une structure *centre riche - première couronne pauvre - deuxième couronne riche*. La structure de la ville dépend de la population totale, des contraintes sur l’usage des sols et de l’inégalité des revenus à l’échelle de l’agglomération. Le modèle donne également des prédictions sur les dépenses logement des ménages.

L’analyse empirique sur les villes des États-Unis montre que ces prédictions sont compatibles avec les observations. D’une part, les ménages à bas revenus dépensent une part plus importante de leur revenu pour se loger que les ménages à hauts revenus, et ce d’autant plus que les inégalités de revenus dans l’agglomération sont élevées. Les dépenses logement augmente avec la population de la ville et les contraintes sur l’usage du sol. D’autre part, les grandes métropoles américaines ont des structures “en U”, où le statut socioéconomique est minimal en première couronne, alors qu’il est élevé au centre et en deuxième couronne.

### Deuxième partie : outils prospectifs pour l'évaluation de politiques publiques

Le **chapitre 4** se concentre sur l'effet des nouvelles infrastructures de transport en commun sur la répartition spatiale des groupes sociaux. La littérature empirique ne permet pas d'identifier un effet systématique des infrastructures de transport : certaines études montrent que le transport en commun, moins cher, attire plutôt des ménages à bas revenus ; d'autres études montrent à l'inverse que l'ouverture de nouvelles lignes s'est accompagnée d'une gentrification des quartiers desservis ; des études soulignent enfin des effets hétérogènes. La principale hypothèse de ce chapitre est que les nouvelles lignes n'augmentent pas l'accessibilité de manière uniforme pour tous les groupes sociaux, car les emplois ne sont pas répartis uniformément dans l'espace selon les groupes. On formalise cette intuition dans un modèle d'équilibre partiel du marché du logement, à l'aide d'une mesure de l'accessibilité à l'emploi spécifique à chaque groupe. Le modèle intègre par ailleurs une représentation du "mélange" des ménages dans les quartiers avec des préférences aléatoires des propriétaires-bailleurs.

Le modèle repose sur l'estimation de trois paramètres clés. Le premier est estimé via un modèle hédonique des prix et des loyers. Deuxièmement, une analyse des déplacements domicile-travail permet d'estimer le paramètre de la fonction d'accessibilité gravitaire. Enfin, l'estimation du paramètre de "mélange" repose sur une analyse rétrospective de l'effet des infrastructures de transport ferré dans l'agglomération parisienne de 1968 à 2010 sur la répartition spatiale des habitants selon la catégorie socio-professionnelle. Pour ce faire, on utilise une base de données créée dans le cadre de la thèse, avec les temps de transport entre chaque paire de communes de 1968 à 2010, reconstitués à l'aide d'un modèle 4 étapes. Mettre en regard l'évolution de l'accessibilité aux emplois avec la composition des communes montre la validité du mécanisme considéré, qui permet d'expliquer pourquoi les précédentes études empiriques concluent à des résultats hétérogènes selon les lignes considérées.

Le modèle et les paramètres estimés sont finalement utilisés pour simuler les effets du GPE, un projet de transport en construction dans la région parisienne. On anticipe que le GPE conduira à une gentrification dans une majorité des communes desservies. Ce modèle peut notamment être utilisé pour concevoir des politiques locales de logement ou d'aménagement afin d'accompagner le projet de transport.

Le **chapitre 5** présente l'architecture d'un modèle "Transport - Usage des Sols" appliqué au Cap, en Afrique du Sud. Ce chapitre a été réalisé dans le cadre d'un projet piloté par la Banque Mondiale en partenariat avec la Municipalité du Cap. L'objectif est de construire un outil versatile, qui peut simuler les effets de plusieurs types de politiques publiques, qui repose sur le formalisme de l'économie urbaine, et qui puisse être utilisé par les acteurs locaux.

La ville du Cap se caractérise par une forte croissance démographique, un niveau élevé d'inégalités de revenus et une forme urbaine très étalée. Environ un cinquième



## Résumé

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des ménages vit par ailleurs dans un logement informel. Le modèle s’appuie sur les mécanismes étudiés dans les chapitres 3 et 4, et intègre différents modes de transport, ainsi que des aménités. Il comprend également une représentation explicite du logement informel. Dans cette représentation, vivre dans un logement informel résulte d’un arbitrage entre accessibilité, prix du logement et confort, avec l’introduction d’un paramètre de “désaménité”. Deux types d’habitat informel sont inclus : l’habitat en “bidonvilles” (*informal settlements*) et le *backyarding*, un phénomène de sous-location d’espace dans la cour d’un logement formel, commun en Afrique du Sud. Le modèle alloue les ménages aux différents types de logement via la résolution un équilibre urbain en ville fermée. On estime les principaux paramètres en utilisant une vaste gamme de bases de données, issues du recensement et de sources administratives, et en mobilisant des approches structurelles.

Le modèle peut notamment illustrer comment des politiques d’urbanisme ou de transport peuvent avoir des conséquences involontaires sur l’informalité. À titre d’exemple, nous simulons les effets potentiels d’une politique de “ceinture verte” dans un scénario de référence sur la période 2011-2040. Dans ce scénario, une ceinture verte contraignant l’étalement urbain pourrait augmenter significativement le nombre de ménages vivant dans des logements informels. Ce modèle peut être utilisé pour simuler plusieurs politiques d’aménagement et de transport, et mettre en lumière d’éventuels arbitrages ou synergies entre objectifs d’efficacité et d’équité.

## Conclusion

La modélisation des processus de répartition spatiale des ménages afin de simuler des effets de politiques publiques suppose d’avoir une bonne compréhension des mécanismes sous-jacents. Cette thèse propose dans sa première partie une revue sur les principaux mécanismes de répartition spatiale, ainsi qu’une contribution théorique originale liant l’équilibre urbain à la structure interne d’une ville via une contrainte “d’abordabilité” du logement. La deuxième partie de la thèse propose une application via la conception d’outils permettant des analyses prospectives. Deux modèles sont proposés, qui diffèrent principalement par leur degré de complexité : l’un vise à analyser uniquement une infrastructure de transport en commun, et repose sur l’analyse d’un mécanisme particulier, quand l’autre propose un modèle intégrant plusieurs mécanismes et pouvant être utilisé pour simuler les effets de plusieurs types de politiques publiques.

La thèse ouvre des perspectives de travaux futurs, en particulier pour intégrer une localisation endogène des activités économiques ou des effets d’équilibre inter-agglomération. L’évaluation d’impacts redistributifs de politiques urbaines pourrait également être enrichie pour différencier entre propriétaires et locataires, et prendre en compte le fait que le logement a également une valeur patrimoniale.

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Plaisir non partagé n'est plaisir qu'à moitié : faire sa thèse au CIRED est avant tout

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# Chapter 1

## Introduction

*In a time when family, friends and co-workers are a call, text, or email away, 3.3 billion people on this planet still choose to crowd together in skyscrapers, high-rises, subways and buses. Not too long ago, it looked like our cities were dying, but in fact they boldly threw themselves into the information age, adapting and evolving to become the gateways to a globalised and interconnected world. Now more than ever, the well-being of human society depends upon our knowledge of how the city lives and breathes.*

Edward Glaeser, *Triumph of the City*

For the first time in history, more people now live in cities than in rural areas. Urbanization has been one of the most significant trends in the past decades, and is expected to continue at a robust pace in the decades to come. While urbanization undoubtedly contributes to economic growth, it is also associated with rising local inequalities and the risk of exclusion and relegation for a part of the population. More than ever, we need to understand what can be done to make cities more efficient, greener, and in the same time more inclusive.

At the local or national scale, housing, transport, and planning policies can be implemented by decision-makers to reach these objectives. This dissertation aims at providing insights on how to anticipate the impacts of these policies at the metropolitan scale, based on the framework of urban economics. The long term objective, that expands beyond what is in this dissertation, is to assess the distributional effects of urban policies, that is, the differentiated effects on agents with different levels of income, wealth, or other socioeconomic characteristics.

This introduction presents the general context that motivates the present work, and introduces the main research question. In section 1.1, we show that, as cities are growing globally, low-income inhabitants tend to bear growing housing and transport costs. Section 1.2 presents the challenges associated with *ex ante* policy evaluation and motivates the need for relevant economic models. Finally, after a state of the art of existing models, section 1.3 states the research objective and outlines the content of the four chapters of

this dissertation.

## 1.1 An urban world

### 1.1.1 The growth of cities

The United Nations (UN) considers that the world has been more *urban* than *rural* since around 2007. The 2018 revision of World Urbanization Prospects estimates that 55% of global population now lives in urban areas. This share is expected to reach 68% in 2050, meaning that in the next 30 years, cities would add up to 2.5 billions new residents (United Nations, 2018).

This aggregate number hides important disparities between regions. 90% of the projected growth in urban population by 2050 is expected to occur in Asia and Africa and only three countries - India, China and Nigeria - would account for 35% of it. On the other hand, North America, Latin America, and Europe are already largely urbanized and do not face strong demographic growth.

The pace of city growth around the world - and in particular the pace of urbanization in Africa and Asia - is unprecedented in history, raising multiple questions about its consequences. The largest metropolitan areas are now larger than they have ever been. In 2018, there were 33 cities with more than 10 million inhabitants (United Nations, 2018). Managing human settlements at such scales raises new challenges for urban planning and transportation.

Rural-urban migrations have important cultural, political, or social causes, but urbanization can also be analyzed as an economic phenomenon (World Bank, 1991). This has been at the core of the geographic and urban economics, following the seminal works of Alonso (1964) on the one hand, Krugman (1991) on the other. Using tools from microeconomic analysis, geographic and urban economists model location decisions of firms and households, in particular with regards to transportation costs. Such decisions, when aggregated at the macro level, explain spatial patterns of human settlements and economic activity. Within this framework, urbanization results from “*a complicated balance of forces that push and pull consumers and firms until no one can find a better location*” (Fujita and Thisse, 1996)

One of the key *pulling* forces for urbanization is cities’ advantage in production. The agglomeration of economic activity permits labor specialization, access to more diverse goods and services, and knowledge spillovers (Duranton and Puga, 2004). All these sources of economies of agglomeration make firms more productive in large cities (Combes et al., 2012) and yield higher wages. Urbanization is associated with structural transformations of the economy, as labor moves from the primary sector, in particular because of productivity gains in agriculture, to industry and services. Moreover, households, businesses and public institutions benefit from economies of scale in cities, where density reduces the (per capita) costs of infrastructure provision.

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On the other hand, congestion on the land market increases the prices of housing and drives businesses and households away from the centers, where they bear high commuting costs. The concentration of populations and activities also generates local negative externalities, such as pollution or noise. Cities are costly and polluted, and the disadvantages in consumption and quality of life act as a *pushing* force for urbanization (Fujita and Thisse, 1996; Tabuchi, 1998).

To this view, however, academics have also argued that modern cities are also places with (some) consumption and quality of life advantages. Proximity may enhance social interactions. Pooling of people favors matching, not only on the labor market, but also for romantic partners (Gautier et al., 2010). Urban residents also value the diversity of consumption opportunities and amenities available to them. Economies of scale also increase the quality of specific amenities, such as museums or theaters (Glaeser et al., 2001).

The urbanization of the world shows us that, on aggregate, *pulling* forces are winning. This does not mean that agglomeration is not associated with costs. On the contrary, as people are incentivized to move to cities by employment opportunities, high wages, and urban amenities, these costs become increasingly problematic.

### 1.1.2 The “costs” of agglomeration

This dissertation focuses on the costs of agglomeration and the policies that can alleviate them. These costs are of three types: (i) high housing costs, (ii) long and costly commutes, and (iii) negative externalities associated with density (e.g. pollution, noise).

Housing costs depends for a large part on land prices. The spatial concentration of people and businesses increases the congestion on land, which makes the price per unit of land higher in large urban areas (Glaeser and Gottlieb, 2009). Rising land prices in turn make housing more expensive. In the last decades, housing costs have increased in real terms in many developed countries, a trend that is mostly driven by rising residential land prices (Knoll et al., 2017). Urbanization is accompanied by large divides in housing prices between large metropolitan areas and small cities, and the concentration of households in expensive areas can explain a significant part of the aggregate growth in housing costs (see e.g. Glaeser et al., 2012; Howard and Liebersohn, 2019, in the case of the US).

High housing costs in cities have several consequences. First, households generally consume “less” housing. Dwellings are on average smaller in urban areas and have smaller gardens, if not at all (see e.g. Yi and Huang, 2014, about China). Second, in order to live in a dwelling comfortable enough, households allocate a higher share of their budget for housing. In figure 1.1a, we represent this phenomenon in the case of France. Using data from national expenditure survey (*Budget des familles*), we represent the average share of expenditures for housing, for residents living in urban areas of different sizes, or in rural areas, in 2006 and in 2011. The budget share allocated to housing increases with city size, even though residents in large cities tend to be richer. Moreover, the



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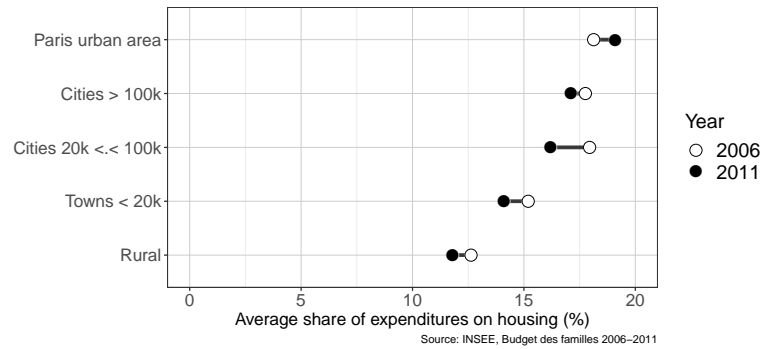
divide appears to grow between Paris and the rest of the country, as the share increased between 2006 and 2011 for the Paris urban area while it decreased everywhere else.

Finally, high housing prices aggravate the trade-off between lower housing costs and longer commutes. In order to pay lower rents or buy cheaper dwellings, households working in large cities can choose to live in remote suburbs, where they face long, and potentially, costly commutes. These interrelations between commuting and housing prices are at the core of urban economics (Alonso, 1964; Fujita, 1989). As cities grow, commuting times tend to increase (Sultana and Weber, 2014). In panel 1.1b, we represent the average time of the journey from residence to work for urban residents in 3 West European countries, using Eurostat data. The size of the circle represents the size of the city. The figure shows that inhabitants of large cities tend to have longer commuting costs. Moreover, the time spent commuting increases over time in many cities. In the United States (US), average commuting time is on the rise, driven by the longer commutes in large metropolitan areas (Siddiqui, 2018). In the Paris region, the average time spent traveling was 76 minutes in 1983. It increased by 21% between 1968 and 2010, to reach 92 minutes (IAU, 2016). This represents a significant challenge for local policymakers, as individuals generally perceive commuting as one of the least enjoyable activities (Kahneman et al., 2004).

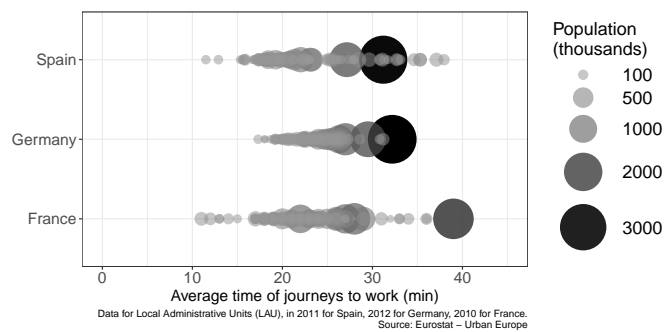
Combes et al. (2018) attempt to provide a systemic measurement of the urban costs, in the case of France. They argue, based on a simple spatial model, that the elasticity of urban costs with respect to city population is “*the percentage increase in expenditure [for housing and transportation] that residents in a city must incur when population grows by one percent, keeping utility constant.*” Using data on French urban areas, they estimate the elasticity of urban costs with respect to city population to range between 0.03 and 0.08.

Urban costs also take the form of negative local externalities. In panel 1.1c of figure 1.1, we illustrate that inhabitants of cities are more exposed to air pollution. We represent the share of residents that are exposed to a high concentration ( $> 15\mu\text{g}/\text{m}^3$ ) of particulate PM10 in European capitals, compared with the average value for their country. For all capitals in the sample except Prague, exposition to air pollution is higher than the country average, in some cases significantly higher. High concentration of PM10, or “coarse particulate matter”, in cities is in particular caused by combustion engines and solid-fuel combustion for energy production in households and industry (Lenschow et al., 2001). Particulate air pollution is associated with serious health effects, including lung cancer and other cardiopulmonary mortality (Cohen et al., 2005). Living in cities is also associated with higher level of crime (Pressman and Carol, 1971; Shelley, 1981), noise (Goines and Hagler, 2007), dirt in the streets, and lack of green spaces. Larger cities tend to exacerbate such negative components of the quality of life (see e.g. European Commission, 2013).

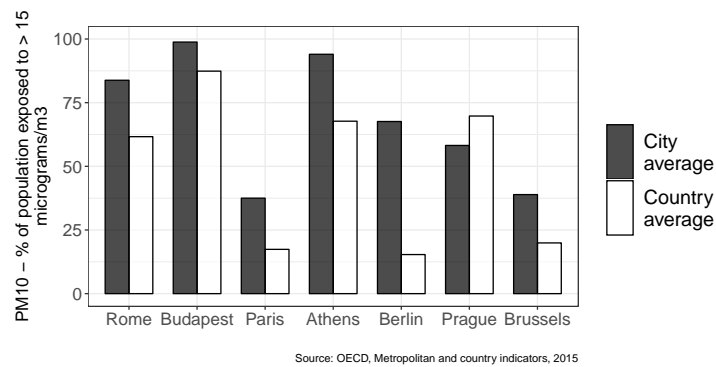
## 1.1. An urban world



(a) Share of expenditures allocated to housing in France.



(b) Average commuting times in cities as a function of city size for 3 European countries.



(c) Exposure to air pollution (PM10) in some European capitals compared to country average in 2015.

Figure 1.1: The “costs” of agglomeration in Europe

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### 1.1.3 Urbanization and inequalities

Although the growth of cities leads to higher aggregate levels of productivity, income, and potentially welfare, the benefits of urbanization, as well as its costs, may not be equally distributed within the population.

The first question is: who benefits more from agglomeration? Larger metropolitan areas tend to have higher levels of income inequality. This is a robust result in the US (Behrens and Robert-Nicoud, 2015). The effect of city size on income inequality can be decomposed into (i) skill sorting and (ii) differentiated effects of city size on productivity across workers. Empirical analysis show that two effects come into play. Large cities disproportionately attract both low- and high-skilled workers, resulting in more unequal distributions of skills (Eeckhout et al., 2014; Baum-Snow et al., 2018). But agglomeration also increases inequalities beyond sorting, as the agglomeration economies increase productivity more at the top of the income distribution (Baum-Snow and Pavan, 2013; Behrens and Robert-Nicoud, 2015). This suggests that high-skilled, high-income workers benefit more from the productivity premium of agglomeration. Income and wealth inequalities are on the rise in many countries (Piketty, 2015) and the differentiated effects of agglomeration economies seem to play a significant role. For the US, Baum-Snow and Pavan (2013) estimate that around a quarter of the overall increase in hourly wage inequality over 1979-2007 is explained by the rapid growth of wage inequality in large metropolitan areas.

A second question is whether high- or low-skilled individuals bear higher costs for urbanization.

High housing prices are a particular burden on low-income households. In figure 1.2, we illustrate this fact by presenting the average share of budget spent on housing in OECD countries in 2014 (or latest year), for households in the bottom and middle quintiles of the income distribution. In all the countries of the sample (except Ireland, for which the shares are almost equal), low-income households spend a higher share of their budget on housing. The difference between the bottom and middle quintiles appears to be particularly high in countries with high levels of inequalities, such as Chile or the US. This result is robust if we consider housing mortgage payment as a share of income (OECD, 2019). This suggests that housing is a *necessity good*, that is a good for which the share of budget allocated to increases with income. Because housing is a necessity, low-income households are more “sensitive” to variations in housing prices.<sup>1</sup>

In order to compete for housing in urban locations, poor residents can choose to rent their dwelling instead of buying them. In many developed countries, homeownership is increasingly correlated with socioeconomic status (Allègre and Timbeau, 2015; Yi and Huang, 2014; Arundel, 2017). This has lasting consequences on the accumulation of wealth. Because housing is a key component of an individual’s capital, the rise in housing prices and the decisions regarding homeownership contribute to the rise in the

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<sup>1</sup>This particular point will be at the core of the model and discussions in chapter 3.

## 1.1. An urban world

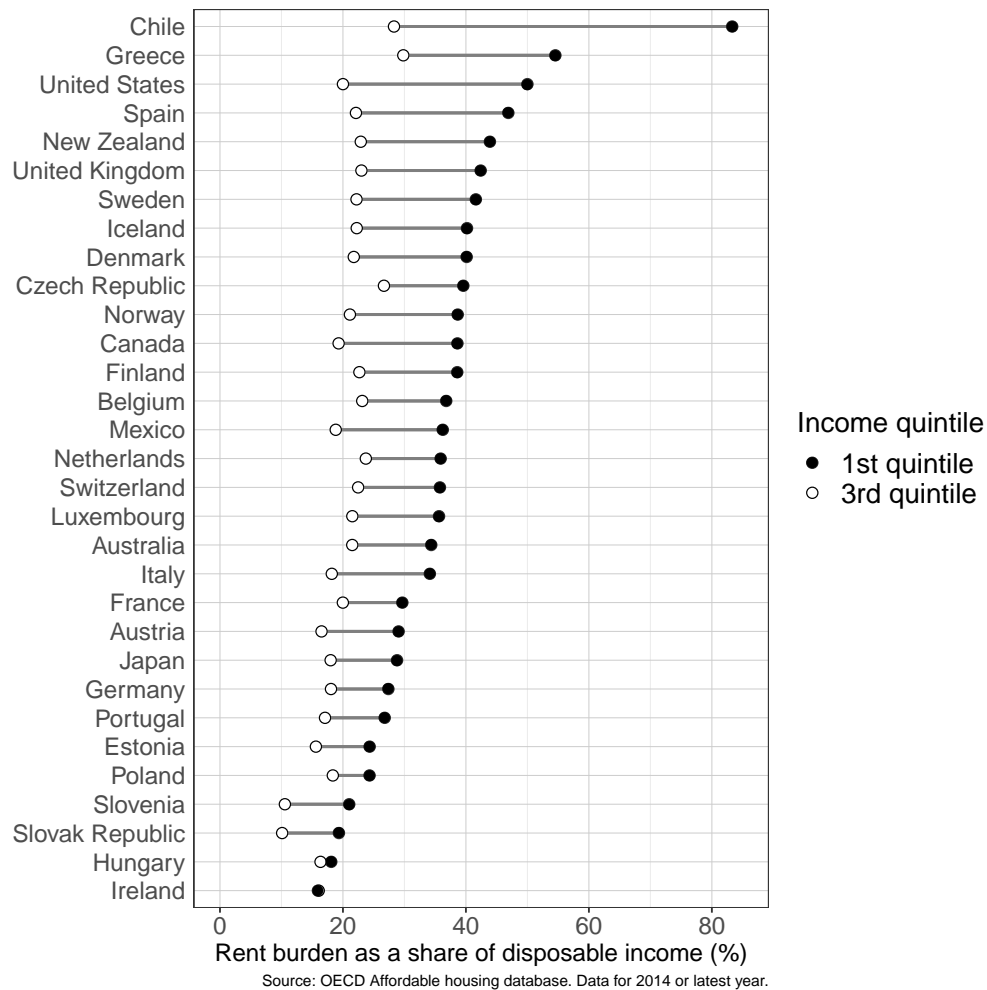


Figure 1.2: Housing expenditure in OECD countries

Note: Figure represents the housing expenditure (for private renters, owners, and subsidized rent) as a share of disposable income for households in the bottom and the third quintile of the income distribution for OECD countries. Source: Affordable Housing Database, OECD.

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wealth-to-income ratio and wealth inequality (Piketty, 2013; Jorda et al., 2019; Fuller et al., 2019).

Another strategy to benefit from urban location is to sacrifice comfort. In the European Union (EU-28), the share of residents that were living in “overcrowded” households<sup>2</sup> was of 15.7% in 2017. The share is 26.5% for people “at risk of poverty or social exclusion” (Eurostat, 2019).<sup>3</sup>

Poor housing condition is a particularly important feature of cities in developing countries. Households that cannot afford a formal dwelling resort to “squatting” of land parcels, resulting in large informal settlements with low housing quality and limited access to infrastructure and public services. The UN estimate that more than 800 million people lived in slums in 2015<sup>4</sup> (UN Habitat, 2016). The growth of slums is a result of both the growth of urban poverty and the lack of affordable housing (UN Habitat, 2003). Living in a slum has important negative outcomes, as slum dwellers tend to be particularly exposed to natural or “urban” risks (e.g. deadly fires), diseases, bad sanitary conditions, or crime (see e.g. the review in Davis, 2006).

In some cases, commuting also places a disproportionate burden on low-income urban residents. This is the case in South African cities, where as a result of decades of Apartheid policies, cities are particularly sprawled out and low-income households live in remote suburbs (the *ex-townships*). This results in particularly long (and costly) commutes for low-income workers, in particular black low-income workers. According to Kerr (2015), while white South African spent on average 54 minutes per day commuting to work in 2003, black South Africans spent 88 minutes.

Finally, multiple examples indicate that low-income urban residents are more exposed to negative externalities of urban life. A large strand of research has documented the existence of “environmental inequality” in US cities (Downey, 2007). For instance, Houston et al. (2004) show that low-income inhabitants of Southern California are exposed to a higher density of nearby car traffic, one of the main sources of air pollution and noise in cities. Low-income neighborhoods also tend to have less access to green spaces (Wolch et al., 2014). Recently, the urban planning institute of the Paris region identified and measured 10 components of environmental quality in the city, 5 negative (air, soil, noise, water, and industrial pollution) and 5 positive (vegetation, ratio of green areas, open

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<sup>2</sup>Eurostat defines a person living in an overcrowded household if he/she lives in a household that “does not have at its disposal a minimum number of rooms equal to: one room for the household; one room per couple in the household; one room for each single person aged 18 or more; one room per pair of single people of the same gender between 12 and 17 years of age; one room for each single person between 12 and 17 years of age and not included in the previous category; one room per pair of children under 12 years of age.”

<sup>3</sup>That is, people living in households where equivalised disposable income per person was below 60% of the national median.

<sup>4</sup>UN-Habitat defines slums as “a contiguous settlement that lacks one or more of the following five conditions: access to clean water, access to improved sanitation, sufficient living area that is not overcrowded, durable housing and secure tenure.” (UN Habitat, 2016)

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areas, collective gardens, and accessibility to parks). Their study shows that low-income residents are over-represented in neighborhoods with more than one nuisance and no or few positive amenities (IAU, 2017). In their own words, “*social and environmental inequalities are closely linked*” in the Paris region.

The rural-urban migration and the growth in urban poverty still indicates that low-income people expect positive outcomes when migrating to cities despite these costs (Eeckhout et al., 2014). However, evidence suggests that, in cities, “housing inequality” and “neighborhood inequality” reinforce wage inequality.<sup>5</sup>

Apart from the poverty “present” in cities, the high costs of urban living may also deter some low- or middle-income residents from moving to cities. This phenomenon is difficult to measure but it can have some strong consequences. A common narrative tend to frame large cities as the future of economic growth and sustainability.<sup>6</sup> Some authors have advocated for policy interventions that enhance growth in cities rather than focusing on unproductive places (Winnick, 1966; Glaeser, 2007). However, a parallel narrative that emerges frames metropolitan areas as increasingly exclusive to high-skilled, high-income people, while the rest is excluded geographically from economic perspectives. The high costs of moving to large cities may be one of the reasons why people remain in economically lagging regions. Bayoumi and Barkema (2019) link diverging housing prices between large metropolitan areas and small towns to a reduction of long-distance migrations in the US. Put together, the two narratives fuel the feeling that not only have economic policies abandoned some areas, but also that it would be too costly for people living in these areas to move to the dynamic cities. Rodríguez-Pose (2018) calls these areas the “places that don’t matter” . He links the economic distress of regions with votes for “anti-elites” parties or policies (such as Brexit in the United Kingdom). He states that “*populism as a political force has taken hold in many of these so-called spaces that don’t matter*”. The resentment induced by unequal distribution of the costs and benefits of agglomeration can therefore have strong political consequences.

Overall, whether it is to improve the quality of life of current urban residents or to enable others to move to cities, designing urban policies that can reduce the costs of urbanization for low-income people is crucial to ensure that urbanization benefits to the majority.

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<sup>5</sup>The distribution of urban costs depends critically on where are the relative groups located within a city. As we discuss in chapter 2, cities are segregated by income and the mechanisms driving the relative location of residents within cities are complex. As noted by Behrens and Robert-Nicoud (2015), this is a frontier of knowledge for spatial equilibrium model of agglomerations. To my knowledge, there is no systemic estimation of the *distribution* of urban costs, such as the one provided by Combes et al. (2018) for a representative agent.

<sup>6</sup>See for example Edward Glaeser’s book *Triumph of the City* and its subtitle: “*How Our Greatest Invention Makes Us Richer, Smarter, Greener, Healthier, and Happier*”.

## 1.2 *Ex ante* assessment of urban policies

### 1.2.1 The challenges for urban policies

In this dissertation, we refer to “urban policies” as the planning, transport and housing policies which may have a significant effect of the housing market and, in the long term, on the urban form, at the metropolitan scale.<sup>7</sup> Many objectives can be pursued by decision makers when implementing such policies: increasing the quality of life by means of affordable housing, making commutes faster or more reliable; attracting new business with affordable office space; but also providing amenities, safety, and efficient public services. Some policies, such as public housing, have explicit distributional objectives. Urban policies have local environmental goals as well, e.g. reducing air and water pollution, which in turn have consequences on public health.

Cities are also at the forefront of large scale environmental challenges, in particular climate change. Responding to the climate crisis requires significant and rapid action to reduce greenhouse gas emissions on the one hand, and to adapt our cities to the effects of climate change on the other. Because urban areas now consume a significant, and growing, share of the land, planning policies also increasingly pursue objectives of preserving natural areas, biodiversity, and agricultural areas. How these environmental objectives interact with other policy objectives is still an important knowledge gap (Seto et al., 2014).

Implementing planning, housing, and transport policies at the urban scale requires to overcome two types of challenges: (i) the systemic interactions within cities and (ii) the high inertia of urban systems.

Cities act as systems, where policies can have important unintended consequences. In particular, an important objective for urban policies is to ensure an appropriate allocation of land, which is scarce in cities. Because several policy objectives are concentrated on land, urban policies have multiple indirect consequences and policymakers may face synergies, or trade-offs, between objectives (Viguié and Hallegatte, 2012). For instance, policies such as urban growth boundaries aim at mitigating urban sprawl for the preservation of natural areas and a reduction in car use. However, they tend to increase the “scarcity” of land, which in turn reduces housing affordability (see e.g. Ihlanfeldt, 2007). In some cases, this may lead to higher density in risk-prone areas (Lall and Deichmann, 2012). Cheshire and Sheppard (2002) also discuss the unintended distributional consequences of planning restrictions, which can be substantial. When choosing to implement such a policy, policymakers face a trade-off between environmental performance, housing affordability, and equity.

Another challenge to overcome is the long lasting effects of urban policies. Structural

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<sup>7</sup>Because urban economics model analyses what happens when “micro” decisions are aggregated at the “macro” level, the tools developed in this thesis are relevant only if they are used on a sufficiently large number of agents. In particular, such tools are not relevant to assess targeted, neighborhood-level policies, nor policies implemented in small cities.

## 1.2. *Ex ante* assessment of urban policies

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modifications in cities occur slowly, over a long time horizon. One key source of inertia is physical, it concerns the building stock and the infrastructure. The spatial organization of a city, its buildings, and its infrastructure is vastly inherited from multiple decisions that were taken in some cases several hundreds years ago. For example, the urban fabric of Paris is still largely shaped by the reconstruction undertaken by Hausmann in the first half of the 19th century. More generally, European cities were built in a time where the automobile did not exist and have dense urban centers with narrow streets, while American cities are more sprawled out and have larger streets (Bertaud and Malpezzi, 2003). This spatial organization is likely to leave its mark for the decades to come. Similarly, the lifespan of a transport infrastructure, such as rail transit systems, can be more than 100 years.

A second source of inertia is social. In section 2, we discuss about the changes that can occur in the socioeconomic status of neighborhoods. Changes are common, but persistence also is. In Cape Town, although the Apartheid ended some 30 years ago, racial segregation inherited from this zoning policy still persists (Geyer and Mohammed, 2016). Moving is costly, therefore residents may not adapt easily to a new situation. For instance, a low-income household that has bought a house in a remote area when the fuel was cheap may face difficult budget issues if the price of fuel increases suddenly. The cost of moving may prevent him from changing its residence location for a more optimal one given the new situation.

Cities are subject to “path dependence”: their spatial organization is the result of many direct and indirect choices, over the long run (Arthur, 1988; Jedwab et al., 2017). As a result, “*once [they have] started down a track, the costs of reversal are very high*” (Levi, 1997). When implementing urban policies, it is therefore important to anticipate on which “track” the urban system will be sent. This is particularly critical for developing-country cities that are growing rapidly: current decisions about building codes, planning, and transport infrastructure will shape them for the decades to come.

### 1.2.2 Economic models to assist decision-making

Socioeconomic evaluation of policies can provide insights to guide local and national decision-making. A popular framework is the Cost-Benefit Analysis (CBA) (Schofield, 1987). By providing a monetary measure for the different social, economic, and environmental impacts of a policy or a project, the CBA gives aggregate values for the expected benefits and costs of a given policy, under one or several future scenario(s). In many countries, the CBA is considered as the reference evaluation process for transport infrastructures (see e.g. Quinet, 2010; Mackie, 2010).

The key challenges for urban policies, presented above, are also challenges for policy evaluation. The anticipation of the effects of urban policies should account for the systemic aspect cities and the potential unintended consequences. Economic models can be useful in this sense, through the notion of “spatial equilibrium”. As an equilibrium is a



## 1.2. *Ex ante* assessment of urban policies

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set of endogenous variables uniquely determined by exogenous parameters, the model enables to compare several outcomes of the system described in two situations (depending on the number of endogenous variables, e.g. land use patterns, prices). As a consequence, economic models often highlight multiple effects of a given policy (for theoretical examples, see Brueckner, 2009).

Economic models also enables the quantification of the effects, which may be useful for three main reasons. First, decision makers may want to compare the benefit of a policy with its cost (this is the core principle of CBA), in order to decide whether a policy is “economically justified”.<sup>8</sup> Second, quantification may help to compare different policy options. For instance, if several routes are possible for a new public transit infrastructure, a modeling exercise can help to determine the best option given the objective(s) pursued. Finally, quantification is useful in a context where multiple forces oppose each other, if one wants to give insights about the resulting outcome (in particular, this objective is at the core of Vigié and Hallegatte, 2012).

Many models exist for quantified assessments of urban policies. One key dimensions along which models differ is their complexity. Complexity range between simple theoretical models with numerical applications (see e.g. Bertaud and Brueckner, 2005) to general equilibrium models of both the residential and productive sectors. One important type of models are Land-Use and Transport Interaction (LUTI) models. LUTI models differ widely, both by their theoretical foundations, their calibration methods, and the type of scenarios that can be simulated (see, for instance, de La Barra and Anez, 1998; Anas and Liu, 2007).<sup>9</sup> Recently, a parallel type of models has emerged in the field of urban economics: quantitative spatial equilibrium models (see e.g. Ahlfeldt et al., 2015; Owens et al., 2017; Tsivanidis, 2018).<sup>10</sup> Authors usually put significant attention of the estimation of the parameters, using complex but more rigorous methods than LUTI models.<sup>11</sup>

Most of the aforementioned models focus on determining the aggregate benefits from a policy or a project (a requirement in order to perform a CBA), and rely on the assumption of a representative agent in the economy (we review in section 1.3 the most important models that do account for heterogeneous agents). We discuss below why introducing heterogeneity, and in particular being able to disaggregate the benefits and the costs between income groups, is an important research objective.

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<sup>8</sup>Note than in a context of CBA, models can also provide estimates of the uncertainties regarding the projected costs and the projected benefits.

<sup>9</sup>Wegener (2014) and Acheampong and Silva (2015) provide useful literature reviews of LUTI models and their main characteristics.

<sup>10</sup>For a review of quantitative spatial models, in both geographic and urban economics, see Redding and Rossi-Hansberg (2017).

<sup>11</sup>The estimations of the model parameters typically rely on exogenous “shocks”, such as the installation and removal of the Berlin Wall in the case of Ahlfeldt et al. (2015).

## 1.2. *Ex ante* assessment of urban policies

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### 1.2.3 Why accounting for income heterogeneity in assessment of urban policies?

Three different types of motivation can be pursued when integrating considerations of income heterogeneity:

**For a better representation of urban dynamics** Our first motivation is the assumption that accounting for income heterogeneity enables for a finer understanding and modeling of cities. In cities with high inequalities, mechanisms related to income heterogeneity may be of first order importance to understand the urban form, the commuting patterns, or the environmental outcomes. Therefore, models with a representative agent may be misleading.

The case study of Cape Town, in chapter 5, is particularly illustrative in this regards. Several decades of Apartheid policies have shaped the urban form of South African cities, which are still marked by strong differences in income. The densest areas in Cape Town are not located where accessibility to employment is the highest, as the standard model of urban economics would predict. However, the densest areas are the ones with the lowest income, as low-income residents have a small *per capita* consumption of land. If mechanisms that prevail in “low-inequalities” cities are of second order in Cape Town, the evaluation of urban policies cannot ignore income heterogeneity, even to measure aggregate effects.<sup>12</sup>

**To design distributional policies** Overall, income and wealth inequalities are on the rise in many countries (Piketty, 2015), in part because of heterogeneous benefits from agglomeration economies, as discussed before. The conjunction of urbanization and rise in inequality makes housing outcomes worse for the poor urban residents. In this context, redistribution and poverty reduction can be explicit objectives of housing policies, but also transport or planning policies. From a normative point of view, policymakers may value equity in itself.

Moreover, a common view is that inequalities have harmful consequences for a society as a whole, not just for the poor (see e.g. Ferreira and Walton, 2006). The debate on inequality has focused on national-level trends in inequality (Piketty, 2015), but many of the negative consequences of inequality may come at play at the local level. For instance, crime is a mostly localized phenomenon that is favored by the concentration of inequalities in a dense area (Glaeser and Sacerdote, 1999). Another negative effect of inequality is

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<sup>12</sup>As an illustration, consider the implementation of *MyCity*, a Bus Rapid Transit (BRT) system built circa 2009. Public transit policies increase accessibility and there is strong evidence that it leads to local increase in housing prices (see the review in chapter 4). However, in Cape Town, public transit is overwhelmingly used by low-income residents and marginally by high-income ones, who commute by cars. Therefore, the implementation of the BRT in high-income neighborhood has led to an actual decrease in surrounding local prices (Beukes, 2016). This could not have been predicted by models that only consider a representative agent.

### 1.3. Objective and content of this dissertation

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associated with the loss in subjective welfare due to conspicuous consumption. This phenomenon has also arguably a local component. As an example, Winkelmann (2012) uses data on Switzerland municipalities to show that the prevalence of luxury cars in the municipality of residence has a negative impact on reported income satisfaction.

Local policymakers may therefore have a strong incentive for redistribution. Because direct taxation and redistribution are generally not available at the local political level, identifying urban policies that may have a progressive effect on the income distribution is an important objective for research.

**To understand the political economy of urban policies** One reason to study the political economy of urban policies is to understand why policymakers implement certain measures whose effectiveness is questionable. Borck and Wrede (2005) make this point about transport subsidies in cities. Authors such as Fujita (1989) and Brueckner (2005) argue that subsidizing commuting to work is not Pareto-efficient as it favors urban sprawl. However, many countries implement transport subsidies. Borck and Wrede (2005) argue that the redistribution of benefits between groups, a political economy mechanism, can explain the popularity of this policy.

The opposite to this proposal is that the political economy can also allow us to understand why some measures theoretically efficient are *not* implemented. If policies are framed as “unfair”, they can be met with resistance. A recent example of such a resistance is the “yellow vests” protests in France, that took place between 2018 and 2019. Early-wave of protesters opposed the increase of the fuel tax, driven by the carbon tax implemented by the national government. Protesters framed the tax as being particularly hurtful to low-income rural and suburban residents, dependent on the car for commuting and errands (BBC, 2018). From a theoretical perspective, fuel tax is a negative transport subsidy. The point made by Borck and Wrede (2005) about transport subsidy arguably has its counter-argument for fuel tax: the distributional impacts of fuel taxes make them difficult to implement. Overall, the “yellow vests” protests suggests that it is crucial to understand the political economy of the environmental transition in order to reduce greenhouse gases emissions.

## 1.3 Objective and content of this dissertation

### 1.3.1 Research objective

The objective of this dissertation is the ex-ante assessment of urban policies, with a specific focus on the distribution of benefits and costs related to commuting and housing.<sup>13</sup>

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<sup>13</sup>One important limitation of the present work is that we do not consider effects on the productive sector. As a result, we do not discuss how economies of agglomerations come at play and are affected by urban policies. Models developed in this work assume incomes and employment locations as given. Moreover, we do not consider the costs associated with negative externalities. All these elements are left

### 1.3. Objective and content of this dissertation

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#### Frame 1.1: Equity and the distributional effects of policies

In the introductory paragraphs, we referred to the “distributional effects” of a policy as the differentiated effects of the policy on agents with different levels of income (or wealth, or other socioeconomic characteristics - see the discussion in chapter 2). This definition of “distributional effects” is restrictive, as it excludes the horizontal component, that is the differentiated effects between agents with the same income.

Since Musgrave (1959), horizontal and vertical equity have been considered as the two sides of the same coin. In particular, horizontal equity can be a relevant concept for the analysis of transport policies (Litman, 1996; Delbosc and Currie, 2011; Camporeale et al., 2017).

Throughout this dissertation, we will restrain our analysis on the vertical component of equity, by comparing the economic outputs for different groups. This

restriction is in part due to one conceptual tool that we rely on: utility equalization. A key assumption of spatial microeconomics models is that utility must be equal everywhere for agents of the same group. This condition for the spatial equilibrium is theoretically appealing and is a useful assumption for empirical models. However, it limits the ability to study horizontal distributional effects.

By comparing utility levels, we can make “vertical” welfare analysis (we do it in chapters 3 and 4). However, such a welfare analysis changes the point of view, from descriptive to normative, and relies on strong assumptions that need to be discussed. For simplicity, we keep the analysis as much as possible on a descriptive point of view: we describe the simulated effects of given policies on specific indicators, e.g. housing types in chapter 5, for each of the groups considered.

Such evaluation of urban policies is at the core of a research program initiated about 10 years ago in the research team where this dissertation was conducted (the CIRED, see e.g. Gusdorf and Hallegatte, 2007; Gusdorf et al., 2008; Vigi  , 2012; Vigi   et al., 2014).

In order to introduce income heterogeneity in economic models of land use in cities, one must introduce differentiated locations for households with different incomes. In practice, rich and poor households do not live in the same neighborhoods. In what follows, we refer to this phenomenon as “income sorting”. Two initial assumptions motivate this dissertation: (i) housing, transport and planning policies induce changes in income sorting and (ii) the relocation of residents has significant effects on the long term distributional effects of such policies.

A significant part of the existing literature on the equity effects of urban policies consider fixed residential locations. This is the case, for instance, for the literature on

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for future work.

### 1.3. Objective and content of this dissertation

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urban road pricing, as reviewed by Levinson (2010).<sup>14</sup> Here, we aim at moving beyond this simplification. Other works focus on the distributional effects of specific urban policies, but keep the discussion on theoretical grounds. For instance, Bento et al. (2006) study the efficiency and distributional impacts of several anti-sprawl policies. Borck and Wrede (2005) discuss who wins and loses from commuting subsidies. Both papers, however, study theoretical cities, with simple urban structures. Though theoretical papers offer insights on the potential unintended effects of policies, they cannot be used for quantitative policy assessment.

Finally, some applied models of the transport and land-use systems include a disaggregation in several socioeconomic groups. Unfortunately, a complete review of how income heterogeneity is accounted for in LUTI models is made difficult by two facts: (i) most of these models do not focus specifically on equity and income sorting, and (ii) many models are not fully documented in the scientific literature. Therefore, the majority of studies relying on LUTI models do not state clearly how the residential sorting is done.<sup>15</sup>

The introduction of income heterogeneity in such models represents a significant challenge. In a review on LUTI models, Geurs and Van Wee (2004) state that “*An in-depth analysis [of equity and social justice effects] would require a disaggregate level of population modelling (split up according to socio-economic groups) at a relatively high spatial resolution, which, at present, is beyond the state-of-the-practice of most land-use/transport interaction models*”. This review dates back to 15 years, and some recent models now incorporate several groups of residents. This is the case of RELU-TRAN (Anas and Liu, 2007), for instance, which has been used to assess the distribution of benefits and costs from specific urban policies (e.g. congestion pricing in Safirova et al., 2006). RELU-TRAN is grounded in microeconomic theory and its structure is fully published in an academic journal (Anas and Liu, 2007). Residential sorting in RELU-TRAN relies on idiosyncratic parameters for each combination of employment, residence, and skill group. Another recent example of well-established simulation model is UrbanSIM, a model with multiple bricks that can be adapted by the end users depending on local context and data availability (Waddell, 2000). In its version with multiple households, the residential choices are simulated using a discrete-choice model where the marginal utilities for each location attribute can be household-specific (Waddell, 2010; de Palma et al., 2014).

The underlying assumption for the specifications of RELU-TRAN and UrbanSIM is that households from different groups have different preferences, either for location attributes or for locations themselves. One advantage of this assumption is that it makes the calibration simpler. Using cross-section econometric regressions, users can estimate

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<sup>14</sup>Another example is Bureau and Glachant (2011), who study the distributional impacts of several potential transport policies for the Paris Region, assuming that there is no effect of the policies on the locations of residents.

<sup>15</sup>As an illustration, the reader may refer to the presentation of the application of MEPLAN to 3 cities in Echenique et al. (1990).

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the parameters associated with each of the spatial features of the city (including accessibility, see e.g. Waddell, 2010). However, these specifications appear disconnected from the theoretical discussions on income sorting. Urban economists have proposed multiple theories that explain patterns of income sorting (see the review in 2). Some of these theories do rely on diverging preferences between rich and poor residents, but many different mechanisms have also been proposed. Under the assumption of heterogeneous preferences, how a given policy alters the relative location of residences mostly depends on past statistical correlations. Moreover, this assumption also carries implications in terms of policy assessment (e.g. welfare analysis) that are often not discussed. As a consequence, these recent LUTI models remain limited in their ability to discuss the distributional effects of urban policies.

Recently, quantitative structural models such as Ahlfeldt et al. (2015) offer a promising approach to urban modeling, that combine theoretical and econometric tools. Such an approach has been primarily used to estimate key economic parameters (Ahlfeldt et al., 2015; Redding and Sturm, 2016) or to build counterfactuals for *ex post* policy evaluation (Redding and Rossi-Hansberg, 2017; Tsivanidis, 2018; Herzog, 2020). Some of the most recent papers using such models include heterogeneous households (Tsivanidis, 2018; Herzog, 2020). To our knowledge, such models are not used for *ex ante* assessment of urban policies, nor to simulate prospective scenarios of urban development.

Although numerous quantitative models of urban land use exist, it appears that the assessment of the distributional impacts of urban policies remain a vastly unexplored field. This dissertation aims at exploring this field, mostly by providing new tools for *ex-ante* assessment of urban policies, based on existing economic literature. An intermediate step towards this objective is to answer the research question: what forces drive income sorting, and how do specific housing, transport, and planning policies affect them?

#### 1.3.2 Our approach

In this dissertation, we place ourselves in the framework of urban economics, particularly in the subfield that studies intra-metropolitan spatial patterns. This line of work gained significant interest in the second half of the 20<sup>th</sup> century following the seminal works of Alonso (1964); Mills (1967) and Muth (1969).

In this framework, individuals' budget or utility is affected by goods that vary with location, in particular accessibility to employment. As a result, agents are willing to pay more or less to live in specific locations. The spatial organization of cities is then the result of the aggregation of individual decisions that are cleared through a land and/or housing market. Urban models with heterogeneous agents can provide insights on income sorting within cities, based on the key assumption that households from different groups *compete* for locations, through the housing market. Because landlords are in positions of local monopoly, land or housing is allocated to the highest bidder in each location. This assumption is at the core of many of the literature reviewed in this dissertation, and is

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used in the models we develop as well.<sup>16</sup>

Note that urban economics is not the only conceptual framework available. Other branches of social sciences also provide theories that relate to residential sorting within cities.<sup>17</sup> However, the existing literature on this subject in all branches of social sciences, including geography, sociology, history, political sciences, and economics, is too wide to be treated in an extensive review. We therefore restrict our scope to urban economics. Doing so, we favor explanations of residential sorting as the result of the aggregation of individual decisions. By expanding the scope of explanations to other disciplines, we could, for example, discuss the role of local communities (Lee and Ousey, 2005), cultural differences between ethnic groups (Nagel, 1994), national or local government interventions (Van Kempen and Şule Özüekren, 1998), the interactions between public and private housing (Musterd, 2005; Arbaci, 2007), or the social and symbolic natures of preferences (Bourdieu, 2000). Although some are mentioned in chapter 2, these mechanisms are mostly left out of the scope of this work.

Our approach is to use tools from urban economics to anticipate of the effects of transport, housing, and planning policies, with an explicit representation of income sorting. We build models with quantitative applications for real-world case studies: Paris (chapter 4) and Cape Town (chapter 5). The two cities represent different contexts. Paris is one of the largest cities in Europe (its urban area represents more than 12 million inhabitants). It is a city with a significant share of historical buildings, in a developed country, with an extensive public transit network. On the contrary, Cape Town is a metropolitan area of around 4 million inhabitants, in a developing country, with an urban structure impacted by several decades of apartheid policies. It has a significant share of informal housing (around 20% of households in 2011). Because the contexts and the research objectives of chapters 4 and 5 differ, the models and approaches used also differ.

#### 1.3.3 Structure of the dissertation

This dissertation is divided into two main parts.

**Income sorting within cities** Part 1 consists of chapters 2 and 3. It discusses the relative location of residents in cities based on socioeconomic characteristics, in particular according to income (“income sorting”). In chapter 2, we present some stylized facts about income sorting and the social structures of cities. We then provide a literature review about the main mechanisms driving the relative location of residents. Multiple mechanisms drive income sorting cities. Some represent “general” mechanism, that explain a

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<sup>16</sup>Note that in chapter 3, we consider “perfect” sorting, that is the group with the highest bid-rent in a location occupies it exclusively. The models of chapters 4 and 5 do include group mixing, through different mechanisms. Chapter 4 relies on a “black box” approach where land owners have idiosyncratic preferences. In chapter 5, income mixing arise from the juxtaposition of housing types in a same location.

<sup>17</sup>See e.g. Van Kempen and Şule Özüekren (1998) for a general review of the different conceptual approaches to segregation.

## 1.4. Coauthors

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regularity in observed patterns, while others link city structures with the idiosyncratic features of each neighborhood. We conclude that urban models must account for both types of mechanisms.

We also conclude from this literature that the existing literature does not provide a uniform explanation for the recent trend of gentrification of inner-city neighborhoods in large metropolitan areas, in both North America and Europe. In chapter 3, we presents a new theoretical model of location by income, that expands the standard monocentric model by introducing inelastic housing demand. This specification for housing demand is consistent with the literature on housing demand and has important implications. First, it predicts that city structure changes as city population and income inequality grow, in a way that is consistent with observations on US cities. Second, we argue that considering housing demand as inelastic is key to the analysis of the distributional impact of urban policies.

**Quantitative tools for *ex-ante* evaluation** In the second part of the dissertation, we design two quantitative models for *ex-ante* evaluation of urban policies. The two models differ by their objectives, their complexity and the methods used for calibration.

In chapter 4, we use a simple, tractable, model to study the effects of new public transit infrastructure on income sorting. We review the existing literature on transit and income sorting, which does not allow to conclude *a priori* on a systematic effect of new transit lines on gentrification. We therefore derive a model for the assessment of future transport projects on income sorting. The simplicity of the model allows us to estimate its parameter using historical data on past openings of rail transit lines in the Paris region. We then apply this model to anticipate the effect of the Grand Paris Express (GPE), a large rail transit project under construction in Paris.

Finally, chapter 5 aims at building an economic-based LUTI model, applied to Cape Town, South Africa. The model of chapter 4 focused on one mechanism to drive the income sorting (accessibility to jobs). On the contrary, multiple mechanisms are integrated in the model of chapter 5. This model was built as part of project funded by the World Bank and with the collaboration of the City of Cape Town. Apart from income heterogeneity, one novel feature of this model is an explicit representation of informal housing. The drawback of greater theoretical complexity is higher uncertainty, both regarding the theoretical construction and the parameters value. We use the model to simulate the impact of an Urban Growth Boundary in Cape Town in several prospective scenarios, as a proof of concept.

## 1.4 Coauthors

Chapter 3 was published as a CIREED working paper and is under submission in an academic journal. It was coauthored with Vincent Vigi  , Julien Deur, and Franck Lecocq.



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For this chapter, I contributed significantly to the theoretical model, the empirical analysis, and the writing. I also made the numerical simulations. I conducted all the analyses in chapter 4 with advices from my supervisors and I wrote the chapter, which is yet to be submitted. Chapter 5 was written as part of a project funded by the Department for International Development (DFID) and was published as a World Bank policy research paper. It was coauthored with Claus Rabe, Harris Selod, and Vincent Viguié. I made the simulations and most of the empirical work. I also contributed significantly to the writing process.

All errors in this dissertation remain my own.

## Chapter 2

# Income sorting within cities

*Any city, however small, is in fact divided into two, one the city of the poor, the other of the rich.*

Plato, *The Republic*

### 2.1 Introduction

A common, perhaps even universal, feature of cities is the existence of sharp differences in income between neighborhoods. We refer to this phenomenon as segregation by income, or “income sorting”. In order to anticipate the potential distributional impacts of urban policies, we must be able to understand to which extent these policies may alter income sorting. This chapter therefore aims at reviewing the urban economics literature about income sorting, and in particular about the mechanisms leading to specific spatial patterns of income sorting.<sup>1</sup>

Most of this literature focuses on North American cities, and more specifically on the United States (US). However, the lessons learned and the mechanisms discussed here are useful for the analysis in other contexts. We also discuss in section 2.4 mechanisms that are specific to cities in developing countries.<sup>2</sup>

Before reviewing the main mechanisms, we present some stylized facts about income sorting (section 2.3). At first glance, there does not seem to be a regularity in the spatial organization of cities when it comes to income sorting. Moreover, different neighborhoods tend to evolve differently over time. Some neighborhoods remain stable in terms of social status, while others change, sometimes abruptly. We discuss in particular the trend of gentrification of inner-city neighborhoods in large metropolitan areas, that appear to be common in North America and Europe, and is also observed in other regions.

Facts about income sorting are not unequivocal and as a consequence theory is not.

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<sup>1</sup>Extensive reviews of the literature already exist on this topic. The reader may in particular refer to contributions by Rosenthal and Ross (2015) and Duranton and Puga (2014).

<sup>2</sup>See also chapter 5, where specific attention is put to the modeling of informal housing.

## 2.2. What is income sorting and why does it matter?

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Multiple mechanisms have been proposed in the literature and there is no consensus on their relative contributions. A recurring theme throughout this chapter is the dichotomy between general mechanisms, that come at play “everywhere”, and idiosyncratic features that make each city, and each neighborhood, unique. Generally speaking, identifying general mechanisms is a key objective for research, and is critical to design prospective models. However, general theories are unlikely to capture the diversity of spatial patterns. We discuss the consequences of this dichotomy in terms of prospective modeling in the conclusion of this chapter.

Another takeaway from this chapter is that the main theories for income sorting do not appear to fully explain the dynamics of gentrification in North America and in Europe. We identify room for extensions of the theoretical literature, that introduce the contribution of chapter 3.

This chapter is organized as follows: section 2.2 defines income sorting and motivates why we give special attention to this matter. In section 2.3, we document some stylized facts about patterns of income sorting observed in cities around the world. We examine in details an important ongoing trend: the gentrification of inner-city neighborhoods in large metropolitan areas. In section 2.4, we review the main theories of location by income within cities in the urban economics literature. Section 2.5 discusses whether the theories presented in section 2.4 can explain the recent trend of gentrification. Finally, section 2.6 concludes.

## 2.2 What is income sorting and why does it matter?

### 2.2.1 Defining income sorting

In this dissertation, we define “income sorting” as the *processes by which residents with different levels of income live separately from one another, in specific locations of the urban space*. We consider that income sorting differs from “segregation by income”, although both are highly related. We characterize segregation by the degree of residential separation of two or more groups, that can be measured by specific indexes (see frame 2.1), and income sorting by specific spatial configurations that result from the separation, for instance: “rich residents live disproportionately in the West side”, or “in the city center”.

Different types of *income* exists. The income that we focus on is the one that conditions the purchase, or the renting, of a dwelling. Authors from the housing demand literature have long argued that the *permanent income* is a better predictor of behaviors on the housing market than the *current income*, since many households use long-term loans to finance the purchase of their dwellings (De Leeuw, 1971; Mayo, 1981; Goodman, 1988). In practice, data about permanent income is not easily available, particularly at the local level. However, permanent income can be well predicted by several variables, that include current income, occupational category, and educational attainment (Good-

## 2.2. What is income sorting and why does it matter?

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man, 1988). These variables are often collected at the local level by census authorities.<sup>3</sup> Therefore, in this dissertation, we will refer alternatively to sorting by different variables describing *Socioeconomic Status (SES)*, such as current income, educational attainment, and/or occupational category, depending on data availability. These indicators are used as proxies for permanent income.<sup>4</sup>

### 2.2.2 Cities are increasingly segregated by income

Social division within cities is an ancient phenomenon, already mentioned by Plato around 375 BC. It gained significance with the emergence of modern cities during the industrial revolution (Vitoux and Kammerer, 2004). Today, segregation by income appears to be a universal feature of urban areas around the world, although its intensity varies greatly across cities. International assessment and/or comparison of intra-urban segregation is made difficult by the diversity of local socioeconomic data formats. Comandon et al. (2018) build a unique dataset for OECD countries, based on the interpolation of national income data. They show that segregation varies greatly between countries, but also (and with a greater magnitude) between cities within a country.<sup>5</sup>

Even though there exists several ways to define and measure segregation (see frame 2.1), recent studies converge on the fact that social segregation has globally shown an overall positive trend, at least over the last decades. Musterd et al. (2017) document the fact that segregation by income increased in European capitals between 2001 and 2011 (see also Tammaru et al., 2015). Taylor and Fry (2012) find similar results for US cities between 1980 and 2010. During the same period, racial segregation decreased (Logan and Stults, 2011; Glaeser and Vigdor, 2012; Taylor and Fry, 2012; Rosenthal and Ross, 2015).<sup>6</sup> Even in South Africa, where the end of state-driven racial segregation is more recent, segregation based on race decreases while income segregation increases (Vermeulin and Khan, 2012; Geyer and Mohammed, 2016).

### 2.2.3 The consequences of income sorting

From an academic perspective, the rise of segregation by income justifies our interest in understanding the causes of income sorting. But cities are not only segregated by income.

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<sup>3</sup>In some context, the race can be highly correlated with permanent income. However, sorting by race may obey to specific mechanisms, therefore we will not consider it as an appropriate indicator in what follows. Similarly, we do not consider age as a good indicator of permanent income.

<sup>4</sup>Note that other authors use indicators of SES not as a proxy for permanent income, but because they are interested in the social status in itself (see e.g. Ley, 1986).

<sup>5</sup>Comandon et al. (2018) also document that larger and more affluent urban areas tend to be more segregated. Another robust finding is that the intensity of segregation varies along the income spectrum, as the rich are on average more segregated than the poor.

<sup>6</sup>However, despite recent trends, “racial isolation” remains prevalent over “income isolation” in the US. As reported by Taylor and Fry (2012), “in 2010, 42% of blacks lived in a census tract that was majority black, compared with 28% of low-income households living in a majority low-income tract and 18% of upper-income households living in a majority upper-income tract.”

## 2.2. What is income sorting and why does it matter?

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### Frame 2.1: Measuring segregation

The general definition of residential segregation is the degree to which two or more groups live separately from one another in the urban environment. This definition, however, hides the fact that groups can be “separated” in multiple ways. The debate on how segregation should be formally defined and measured has been ongoing for several decades (Massey, 2012). Perhaps the most standard indicator of segregation is the dissimilarity index of Duncan and Duncan (1955), that represents the share of members of the minority that would have to

move in order to achieve an even distribution. In practice many other indicators exist and are used by academics. Massey and Denton (1988) provide an extensive review of 20 segregation measures, that captures 5 different dimensions of segregation: evenness (of which the dissimilarity index is a measure), exposure, concentration, centralization, and clustering. More recent contributions include Reardon and Firebaugh (2002); Reardon and O’Sullivan (2004); Hutchens (2004).

They are also segregated by ethnicity, household types, or age. The deliberate separation of “white” and “black” neighborhoods in South Africa and in the US had had long-lasting consequences on the urban structure (Logan and Stults, 2011; Vermeulin and Khan, 2012). Discrimination, although now illegal, may still play a role in access to housing (Ross and Turner, 2005). Apart from ethnicity, the composition of neighborhoods may also differ along housing types. For instance, Thomas et al. (2015) document that the share of inhabitants who are married is significantly lower in the center of London than on its periphery. Why then focus on income?

A focus on sorting by income may be justified by its consequences, in particular the fact that it may exacerbate the economic advantages of the rich as well as the disadvantages of the poor. Two effects may be at play here: (i) mechanisms linked to the composition of the neighborhood one lives in (“neighborhood effects”) and (ii) inequalities in access to spatial resources.

Neighborhood effects include social interactions, local role models and perception of the neighborhood, particularly with regard to crime (Friedrichs et al., 2003). There is a large body of literature, out of the scope of this dissertation, that shows how negative neighborhood effects make existing disadvantages worse when low-income residents are concentrated in deprived areas. To say it simply, *“living in areas of geographically concentrated poverty creates additional problems for residents”* (Atkinson and Kintrea, 2001). Above a certain threshold of concentration of poverty, “epidemics of social problems” can appear (Crane, 1991). The effects are particularly acute for educational attainment and life opportunities (Massey and Denton, 1993). Chetty et al. (2014) show that children

## 2.3. Some stylized facts about intra-metropolitan income sorting

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growing in low-income neighborhoods of segregated cities have a significantly lower expected future income than children growing in less segregated cities. For such reasons, income segregation is often considered by policymakers as more than a mere reflection of social inequalities onto space, but as an issue in itself. Reducing *spatial* inequalities becomes a distributional objective in itself.

Another consequence of spatial sorting is related to the inequalities in access to localized resources or opportunities. These include amenities, public services, economic opportunities, and transport infrastructure. Stokes and Seto (2018) quantify job access in US and show that job access is lagging behind for low-income residents. Inequality in access to employment can have important consequences (Comandon et al., 2018). The “spatial mismatch” hypothesis, in particular, states that low-skilled residents lives further from economic opportunities, and that the physical distance increases their probability of being unemployed (Gobillon et al., 2007). Moreover, as discussed in chapter 1, low-income residents may have lower access to green open spaces, recreational or cultural equipment (Downey, 2007; Wen et al., 2013; Liotta et al., 2020).

For these reasons, income sorting and “neighborhood inequality” adds to wage inequality and exacerbate the economic disadvantage for the urban poor (Comandon et al., 2018). Both income inequalities and segregation appear to be on the rise. This justifies a particular effort from academics to understand the causes and implications of income sorting.

## 2.3 Some stylized facts about intra-metropolitan income sorting

To our knowledge, there is no analysis that documents patterns of income sorting worldwide. The main reason for this is likely to be the different formats of social and income data across countries, which make cross-country comparisons difficult. As a consequence, we will not be able to provide stylized facts about income sorting that cover all regions. More specifically, we paid specific attention to the three countries that make up the case studies in the chapters of this thesis (the US in chapter 3, France in chapter 4, South Africa in chapter 5). This facts will be biased towards these specific countries, but the main messages remain *a priori* valid for other regions.

### 2.3.1 Patterns differ from city to city

Apart from the intensity of the segregation by income, cities also differ in their spatial social patterns. Brueckner et al. (1999) compare Detroit and Paris as examples of a US city, where high-income households tend to live in the suburbs, and an European city, where the suburbs are poorer than the center. However, this simple comparison does not withstand a more detailed analysis.

### 2.3. Some stylized facts about intra-metropolitan income sorting

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On figure 2.1, we display the share of residents with a college degree as a function of distance to the city centers for 6 cities in 4 countries. The share of residents with college education is expressed relatively to the citywide mean. This indicator is used as a proxy for the SES, as discussed in section 2.2. The x-axis represents a classification of tracts by quantiles of distance from the center of the urban area. In order to compare cities with different sizes, quantiles are weighted by the population, so that, for example, tracts in the 5-10 percent ring contain the 10% individuals that live the closest to the center, but exclude the 5%.<sup>7</sup>

Figure 2.1 illustrates how patterns change across cities. In New York City, for instance, the share of college-educated is higher in the center, then decreases in the inner suburbs and increases in the outer suburbs. Glaeser et al. (2008) also noted such U-shaped curves of SES as a function of distance for large US cities. In Detroit, the structure appears to be in accordance to what is described in Brueckner et al. (1999): the SES increases with distance from the center. Paris and London have the structure of the “typical” European cities as described by Brueckner et al. (1999), with a decreasing gradient of SES. Marseille, on the contrary, has a non-monotonic relationship, with relatively low-SES in its center.<sup>8</sup> Therefore, there appear to be a large heterogeneity even across metropolitan areas within the same country. In the United Kingdom, Cuberes et al. (2019) also find that the gradients of income as a function of distance from the city center differ widely across cities. Finally, Cape Town has a very high-SES center and poor suburbs.

This view is obviously incomplete, as income may not be uniform between locations located at the same distance from the city center. Many cities do not exhibit radial patterns of location by income. On figure 2.2, we show the share of residents with a college degree in Paris as a function of latitudinal and longitudinal distance from the center (Notre-Dame). The East-West polarization appears much stronger than the North-South one. Other European cities, such as London, are also historically divided between rich Western and poor Eastern areas (Heblich et al., 2021).

Patterns of relative location by SES are therefore complex and differ from city to city. As will be discussed below, both the complexity of patterns and the lack of empirical regularity represent challenges to identify general mechanisms driving income sorting.

#### 2.3.2 Patterns change over time

In 1942, a report from the Paris Prefecture described the Marais, a central neighborhood of the West Bank of Paris, as “*one of the most visible warts in Paris*” (Backouche, 2019).<sup>9</sup> For the past 100 years, the Marais had been a struggling area, subject to overcrowding,

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<sup>7</sup>See also Hwang and Lin (2016), who use the same indicator for distance and discuss its advantages.

<sup>8</sup>Note that Marseille has arguably a non-monocentric structure, as its urban area (“Unité urbaine”) regroups two major poles: Marseille and Aix-en-Provence, the latter being more upper-class.

<sup>9</sup>In its original French version: “l’une des verrues les plus visibles de Paris” (our own translation).

### 2.3. Some stylized facts about intra-metropolitan income sorting

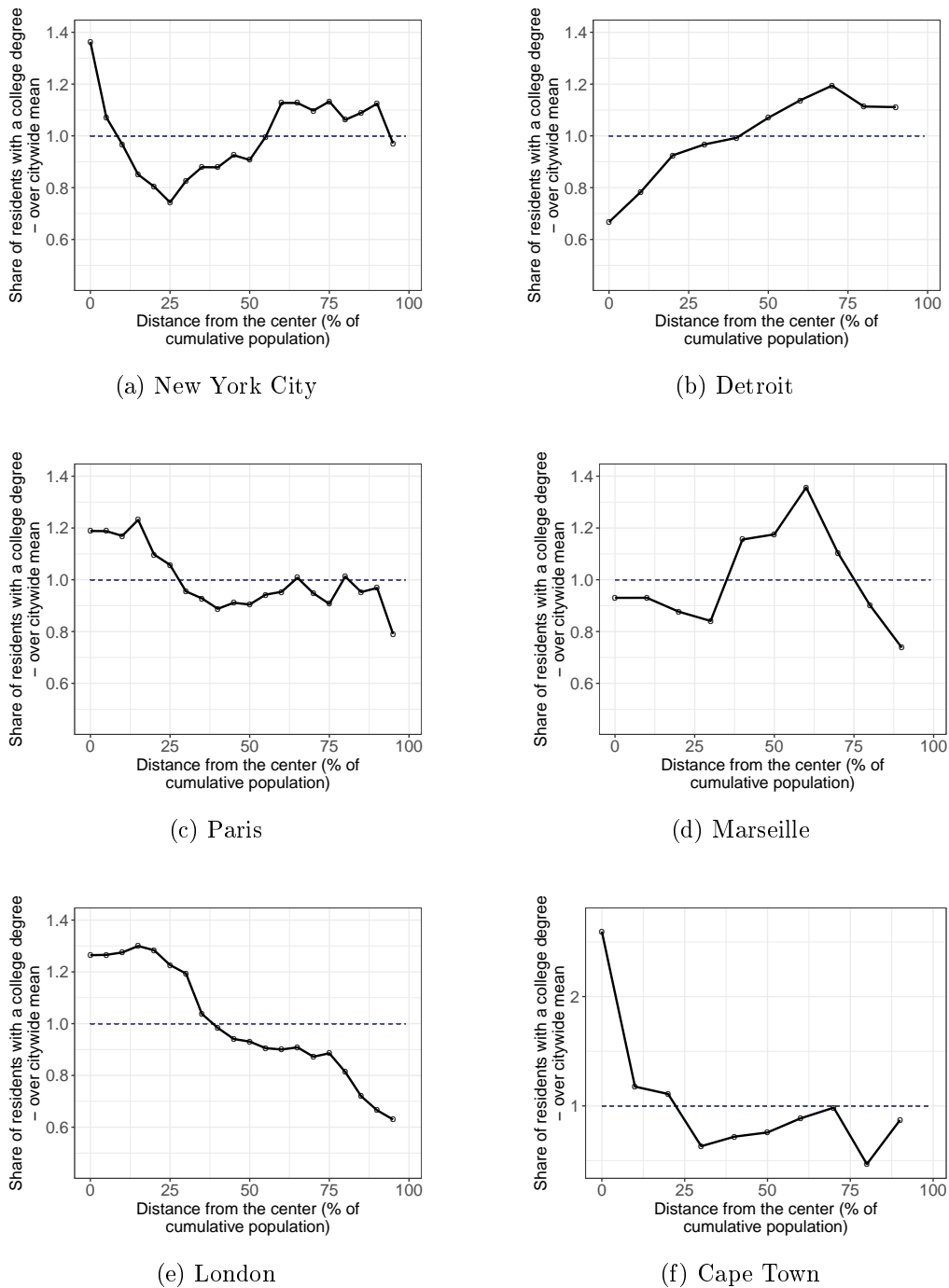


Figure 2.1: Education as a function of distance to the center for sample cities in the world

Note: Figure represents the share of residents with a college degree (over citywide mean) as a function of distance to the city center, expressed as the share of cumulative population. Source: 2016 American Community Survey (ACS) at the Census Tract level for US cities; Census 2015, at the IRIS level for France. 2011 Census at the Output Area level for London; 2011 Census at the Sub-Place level for Cape Town. For US Cities, the y-axis is the relative share of residents aged 25-64 with a college-degree. For French Cities, the y-axis is the relative share of residents aged 15 or more that are not going to school with a college-degree. For London, the y-axis is the relative share of residents aged 16 or more with a college-degree. For Cape Town, the y-axis is the relative share of residents with a college-degree.



### 2.3. Some stylized facts about intra-metropolitan income sorting

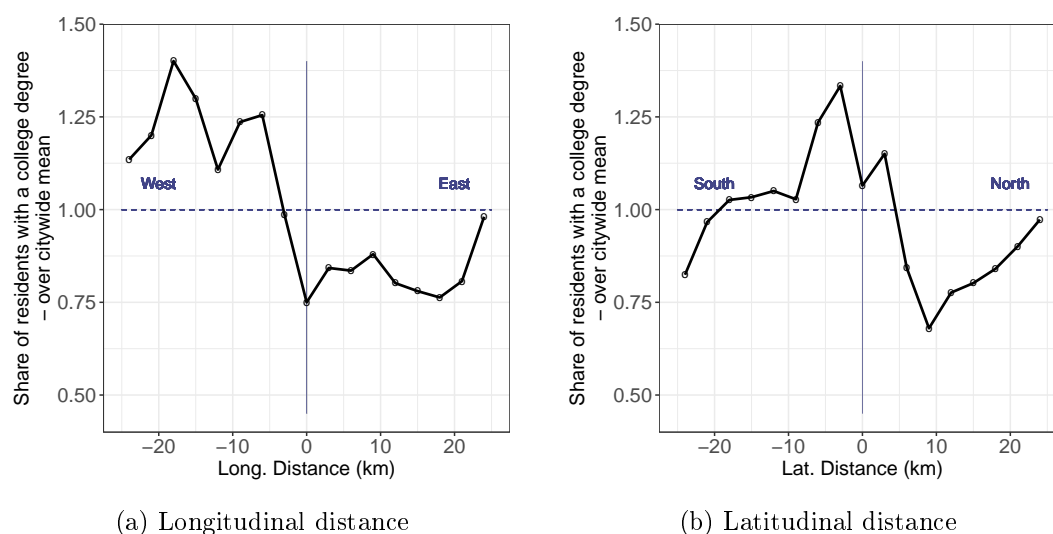


Figure 2.2: East-West polarization in the Paris region

Note: Share of residents with a college degree in Paris (over citywide mean) as a function of longitudinal (X) and latitudinal (Y) distance from Notre-Dame. Data at the IRIS level. The y-axis is the relative share of residents aged 15 or more that are not going to school with a college-degree. The geographical limit is the Urban Area (“Unité Urbaine”)

housing deterioration, bad hygiene, and epidemics. In 2019, around 80 years later, the business newspaper “Les Echos” praised for real estate investment in the same district by describing it as a “*fortress of elegance*” and by stating that “*the Marais is particularly popular with foreign customers looking for a prestigious address*”.

Other neighborhoods decline, sometimes fast. In South Africa, the Hillbrow district was advertised in the early 20<sup>th</sup> century as the future “*healthiest and most fashionable suburb of Johannesburg*” (Morris, 1999). It remained a vibrant inner-city neighborhood until the 1980s. However, between the 1980s and the end of the 1990s, Hillbrow knew some rapid changes in the racial composition of its population along with a severe decline in the housing conditions (Stadler and Dugmore, 2017). Nowadays, the Wikipedia page states that Hillbrow “*is known for its high levels of population density, unemployment, poverty, prostitution, and crime*”.

Such stories of spectacular rise or fall of neighborhoods are not isolated cases. Inner-city decline has also been a feature of many US cities during the second half of the 20<sup>th</sup> century. During the “urban flight”, population socioeconomic status of neighborhoods decreased in city centers while high-SES residents moved to the suburbs (Mieszkowski and Mills, 1993). The decline of city centers has been spectacular in cities such as Detroit, that lost around half of its population between 1950 and 2000.

Overall, despite important historical inertia, changes over time in the relative socioeconomic status of neighborhoods are common. Neighborhoods may get richer or poorer in absolute terms, with strong links with metropolitan- or national-level dynamics. Neighborhoods also change in terms of *relative* socioeconomic status, that is changes relative

### 2.3. Some stylized facts about intra-metropolitan income sorting

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to other neighborhoods of the same urban areas. For the US, Rosenthal (2008) compares each tracts' median income with the percentile of the city-wide income distribution and defines four income categories for census tracts. He calculates that more than a third of low-income census tracts (relative to city-wide income) in 1950 became upper-middle or high-income tracts in 2000; and more than a third of high-income tracts became lower-middle or low-income tracts in 2000<sup>10</sup>, suggesting that relative changes in income are very common, at least over the long run.

As noted by Lee and Lin (2017), neighborhoods are heterogeneous in their propensity to change, both across metropolitan areas but also within the same metropolitan area. For instance, they show that there has been more persistence in spatial patterns of income in Los Angeles than in Dallas between 1970 and 1980. Moreover, high-income neighborhoods in big US cities have been remarkably stable in terms of SES between 1960 and 2010 (Hwang and Lin, 2016). Similarly, Heblich et al. (2021) find non linearities in the persistence of social status of neighborhoods for cities in the United Kingdom (UK).

#### 2.3.3 The gentrification of central areas in large cities: a global trend?

Identifying general trends among the diversity of local contexts and providing explanations remains an important objective for research. In this section, we discuss the trend of gentrification (see frame 2.2 for a definition). The gentrification of inner-cities in large urban areas appears to be a significant trend ongoing in many, if not all, large metropolitan areas in North America and in Europe. Although most of the literature documenting this trend is focused on the US and Canada, cities in other regions may also be concerned, either because similar phenomena are under way or because they may occur in the future.

The term of “gentrification” has been coined by the American sociologist Ruth Glass to describe changes in London (Glass, 1964). Since then, the concept has had important success. On figure 2.3, we use Google Trends data to illustrate that the concept of gentrification has received growing attention in the recent years. Google Trends provides the share of researches made on the search engine Google that include a given word. We plot the share of researches for “gentrification” worldwide, on Google News. For comparison, we also include “segregation” and “urbanization”. Although the word has existed for more than 50 years, it was barely researched in 2008 compared to 2019. The increase is stronger for “gentrification” than for “segregation” or “urbanization”. This shows that either the phenomenon has become increasingly significant and/or that public awareness has grown. In both cases, this suggests that the subject is becoming more and more prominent in the discussions on cities.

In particular, the concept of gentrification has received considerable attention in the US. This is understandable as the gentrification of inner cities, sometimes also referred

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<sup>10</sup>Their estimates is for 35 Metropolitan Statistical Area (MSA) that did not experience changes in their geographic definitions during the period.

### 2.3. Some stylized facts about intra-metropolitan income sorting

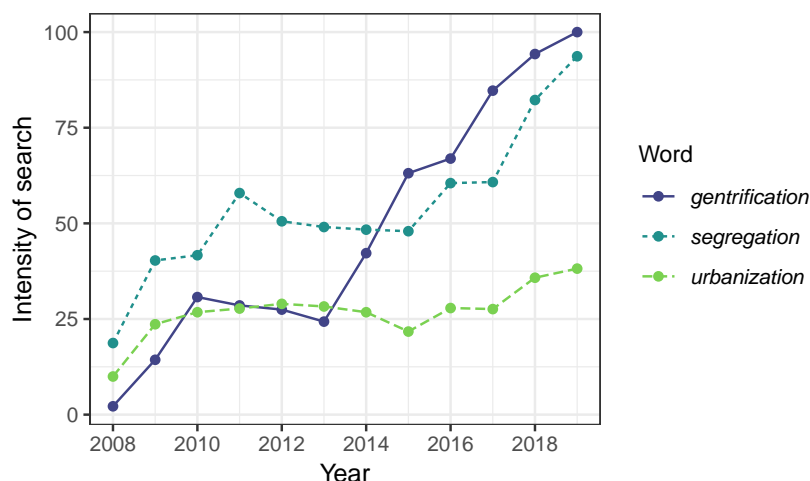


Figure 2.3: Researches on Google News for “gentrification”, “segregation”, and “urbanization”

The y-axis is the “intensity of research” for the words, that measures the share of researches that included the words. Source: Google Trends (2019).

to as “renewal” or “revitalization”, has been a significant inversion of dynamics. In the post-war period, SES decreased in inner-city neighborhoods of US cities, as a result of the “urban flight”, sometimes spectacularly. However, from the 1980s onwards, this dynamic has reversed, with an influx of inhabitants of higher SES in inner-city neighborhoods of New York, San Francisco, and Chicago (Smith and Williams, 2013; Lees, 2008). In the 2000s, this trend became common to most large US metropolitan areas (Baum-Snow and Hartley, 2015; Hwang and Lin, 2016).<sup>11</sup> In fact, between 2000 and 2010, the share of college-educated increased faster in the central areas of the 50 largest US cities than in their suburbs, a trend mostly driven by the location choices of young college-educated (Couture and Handbury, 2017). Hwang and Lin (2016) note that there is significant heterogeneity among tracts within the same metropolitan area, as well as across metropolitan areas. On average, the increase in SES in downtown areas is more pronounced for large cities than for small ones. In chapter 3, we present evidence that this trend has been ongoing between 2010 and 2016, with similar features (mostly in large metropolitan areas).

Although to our knowledge, there exists no worldwide systematic study of gentrification of inner cities, evidence from other cities in the world suggest that this dynamic is not exclusive to US cities (see e.g. the numerous examples in Atkinson and Bridge, 2004). For instance, Thomas et al. (2015) document similar patterns of reversal of demographic dynamics in city centers in the United Kingdom: city centers began regaining population from the 1990s onward and, in large cities, this gain in population was mostly driven by

<sup>11</sup>See in particular Baum-Snow and Hartley (2015), who document the trend inversion for the share of college-educated in inner cities compared to the suburbs.

### 2.3. Some stylized facts about intra-metropolitan income sorting

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#### Frame 2.2: Defining gentrification

The term of “gentrification” is both used in economics, sociology, geography, and political science. As a consequence, it has several formal definitions but, in general, it refers to the influx of affluent residents or businesses in a neighborhood, leading to an increase in socioeconomic status. Details of the definition differ according to the study, the context, and data availability. Gentrification generally implies that the neighborhood is initially of low socioeconomic status, although this condition is not met by all indicators of gentrification used in the literature. For some authors, gentrification also involves changes in the racial composition of the population (e.g. Baum-Snow and Hartley, 2015). Other than population in itself, gentrification may be associated with the physical renovation of the streets, changes in local stores and amenities, new high-end housing units

or rising rents (Smith, 1979). Some authors have used several of these features to build composite indicators of gentrification (e.g. Ley, 1986; Baum-Snow and Hartley, 2015).

In chapters 2, 3 and 4 of this dissertation, we define “gentrification” as an *increase in SES of a neighborhood, relatively to other neighborhoods in the same urban area*. Therefore, if an urban area gets richer, or more educated, as a whole, we will not consider that all neighborhoods are gentrifying. We focus on the composition of the population rather than on other attributes of the neighborhood. In particular, following Brummet and Reed (2018), we consider that rise in rents or housing prices do not necessarily coincide with changes in the composition of the population and is therefore not a satisfactory indicator.

educated individual (and overwhelmingly by educated individuals in London, compared to the rest of the UK).

Reports of similar phenomenon also exist for cities in developing countries (see e.g. Lees, 2014, for a review). For instance, Visser and Kotze (2008) review empirical observations of localized gentrification in inner-city neighborhoods in South Africa, particularly in Cape Town. However, as noted in Lees (2014), the processes and patterns of gentrification in developing countries may differ from gentrification in North American or European cities.

The counterpart of the higher socioeconomic status of city centers is a “suburbanization of poverty”. Kneebone and Garr (2010) show that growth in suburban poverty has been particularly strong for large metropolitan areas between 2000 and 2008 (see also Cooke and Denton, 2015, on a longer period). Growth in suburban poverty has also been documented for large cities in England and Wales (Hunter, 2014), the Netherlands (Hochstenbach and Musterd, 2018), Sweden (Hedin et al., 2012), Canada (Hulchanski

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et al., 2010), and Australia (Randolph and Tice, 2014). In chapter 4, we show that, in the Paris urban area, residents from low-income occupational categories now live on average further away from the center than in 1968, a trend observed with a much lower magnitude for high-income occupational categories.

To what extent the relative enrichment of the centers of large metropolitan areas, with the associated impoverishment of their suburbs, is a global trend remains an open question. Many researchers have highlighted the differences between the forms and processes between countries (Préteceille, 2007; Lees, 2014). Even though each city has its own specific context, the extent of this phenomenon raises the question of whether the underlying mechanism(s) are common.

## 2.4 What drives income sorting in cities?

This section presents the main theories of income sorting, mainly in the economic literature. This literature review will serve two purposes: (i) to understand to what extent the existing literature can account for the observed spatial patterns and local dynamics discussed above, and (ii) to be a roadmap for the modeling exercises of chapters 4 and 5.

This section begins by putting the notion of competition for space, central in urban economics, into historical perspective. We then review the theories that have been gradually established in this field of literature following the canonical model of Alonso (1964); Mills (1967) and Muth (1969).

### 2.4.1 Urban ecology and the competition for land

In the 1920s and 1930s, geographers and sociologists in the Chicago school laid the foundations of the “urban ecology”. Using theory, fieldwork, and data analysis, they showed how behaviors and belonging to social groups are linked to the urban environment. In particular, cities are not homogeneous spaces. They are “*differentiat[ed] into natural economic and cultural groupings*” (Burgess, 1925). Using schematic maps, Burgess (1925) proposed a generic model of the spatial organization of US cities, shown in figure 2.4. The city is divided both socially and functionally, mainly in concentric rings, with specific areas (e.g. “ghetto”, “chinatown”). The business centre is surrounded by a high-density area where recent immigrants and ethnic minorities live together, itself surrounded by increasingly well-off residential areas towards the periphery. Later, other authors proposed variations on the basis of the descriptive model of Burgess, in particular Hoyt (1939) and Harris and Ullman (1945).

Geographers from the Chicago school applied concepts from plant ecology and biology to cities. (McKenzie, 1925) writes “*the plant ecologist is aware of the effect of the struggle for space, food, and light upon the nature of a plant formation, but the sociologist has failed to recognize that the same processes of competition and accommodation are at work determining the size and ecological organization of the human community*”. Following

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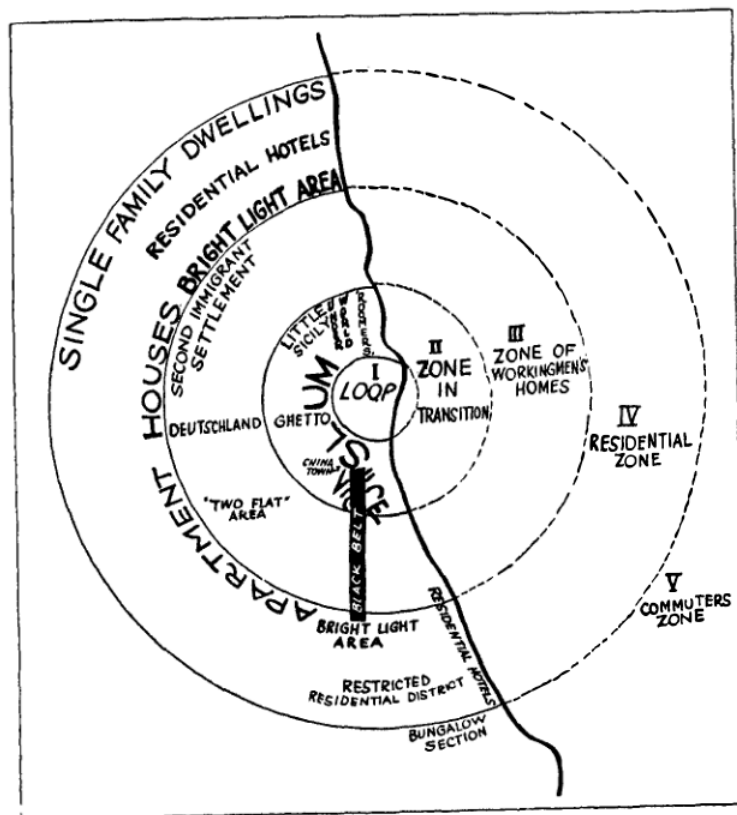


Figure 2.4: The spatial organization of urban areas, from Burgess (1925)

## 2.4. What drives income sorting in cities?

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this intuition, the social and functional division of the city results from the competition between groups for access to resources, in particular land. The status of the different areas changes as a result of a dynamic process of invasion, resistance, abandonment and adaptation.

Many of the results and intuition from the Chicago school laid the foundations for the later models of urban economics. In particular, the competition between groups for land is a central assumption of spatial models in microeconomics presented hereafter.

### 2.4.2 The Alonso-Mills-Muth model

The Alonso-Muth-Mills (AMM) model of residential choice is the first microeconomic model aiming at studying the spatial organization of cities. It relies on several elements (for an extensive review of the AMM model, see Fujita, 1989; Duranton and Puga, 2014). First, households value accessibility to the city center, where all the jobs are assumed to be located (“monocentric” city). Second, the spatial equilibrium implies that the differential of land/housing rent is compensated by the differential in commuting costs (sometimes referred to as the Alonso-Mills condition). Assume that households derive utility  $u(z, q)$  from the consumption of a composite good  $z$  and housing  $q$ .<sup>12</sup> They bear a commuting cost  $t$  that increases with distance to the center  $x$ . The price of the composite good is set at 1 and we denote  $\Psi$  the bid-rent of households in  $x$ . The Alonso-Mills condition is:

$$\frac{\partial \Psi}{\partial x} = -\frac{1}{q} \frac{\partial t}{\partial x} \quad (2.1)$$

Equation 2.1 gives one of the key predictions of the AMM model: rents decrease with distance to city centers. Although this is not detailed here, the AMM model also provides other empirically relevant predictions. In particular, built density and population density decrease with distance to the city center.<sup>13</sup>

Extensions of this model with two types of residents, *rich* and *poor* ones, yields predictions about their relative locations. We assume that households compete for land (or housing) and land owners rent out to the group with the highest bid-rent in each location.<sup>14</sup> In this context, the sorting of individuals based on their income depends on how the slope of bid-rents varies with income. Figure 2.5 illustrates intuitively this point. If the bid-rent gets steeper as income increases, rich individuals live in the center, and poor individuals live in the suburbs. Assume that the transport cost  $t(x, w)$  also

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<sup>12</sup>The utility function is assumed here to be well-behaved, as defined in Fujita (1989). In chapter 3, we derive a model with a utility function that is not well-behaved, leading to greater complexity for the existence and the uniqueness of the equilibrium.

<sup>13</sup>Another prediction of the model, in the closed-city case, is that the more populated the city is, the more sprawled out it is and the higher the rents. This property of the model is discussed in particular in the model of chapter 3.

<sup>14</sup>Note that this model results in a completely segregated city. Tabuchi (2019) discusses the *segregation* and *colocation* of inhabitants with different income in a monocentric model. We also discuss this assumption (and relax it) in the model of chapter 4, that is not *per se* a monocentric model.

## 2.4. What drives income sorting in cities?

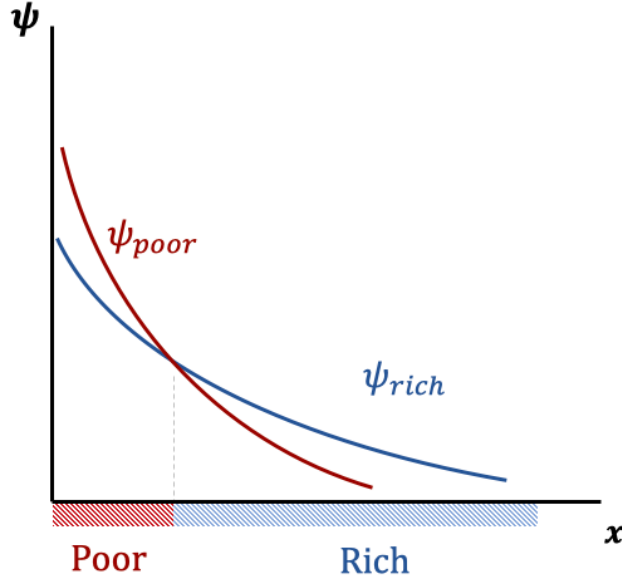


Figure 2.5: Structure of the city predicted by the AMM model, in the case  $\varepsilon_{q,w} > \varepsilon_{t,w}$ .

depends on income  $w$ . Then, differentiating 2.1 with respect to income leads to the following condition:

$$\frac{\partial^2 \Psi}{\partial x \partial w} = \frac{1}{wq} \frac{\partial t}{\partial x} (\varepsilon_{q,w} - \varepsilon_{t,w}) \quad (2.2)$$

where  $\varepsilon_{q,w}$  is the income-elasticity of housing demand and  $\varepsilon_{t,w}$  is the income-elasticity of commuting costs.<sup>15</sup>

Equation 2.2 yields the key result: *income sorting is determined by the comparison between the income-elasticity of housing demand and the income-elasticity of commuting costs*. As an individual's income increases, two forces compete: his commuting cost increases, which attracts him towards the center, but his demand for housing increases as well, which makes the congestion on land more costly for him and pushes him away from the center. If  $\varepsilon_{q,w} > \varepsilon_{t,w}$ , the “housing effect” wins, therefore rich individuals live in the city's outskirts and poor ones in the center.

This result is theoretically elegant and its prediction may lead to interesting discussions. For instance, Fujita (1989) compares Japanese cities and US cities. He argues that the tendency for wealthy inhabitants to live in the center of Japanese cities may be explained by the fact that, in contrast with the US, Japanese employers subsidize commuting of their employees.

The prediction of this criterion depends on the comparison between two economic

<sup>15</sup>Housing demand increases with income if the utility follows standard assumption of normality, therefore  $\varepsilon_{q,w} > 0$ . Similarly, transport costs increase with income if individuals value not only the monetary cost of commuting, but also the time spent, following Becker (1965), leading to  $\varepsilon_{t,w} > 0$ .



## 2.4. What drives income sorting in cities?

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parameters. To our knowledge, only two studies have tried and estimate the two income-elasticities in a way that can be compared. Using data on the San Francisco metropolitan area, Wheaton (1977) estimates that the income elasticity of land consumption and transport are very close (around 0.25). He concludes that the income-elasticity criteria is ambiguous when applied empirically. In a more recent study, Glaeser et al. (2008) estimate that the income elasticity of land demand is between 0.2 and 0.5. They argue that the time cost is overwhelming in the cost of transport and, based on Becker (1965), its income elasticity should be close to 1. They therefore conclude that the AMM condition predicts that high-income households locate in the center, which is not in line with empirical observations about US cities.

Other studies have provided estimates for the income-elasticities separately. The fact that the income elasticity of housing demand is below 1 is robust from several studies in the housing economics literature (De Leeuw, 1971). Using the American Housing Survey between 1985 and 2011, Rosenthal (2014) finds an income-elasticity of 0.124 for rented units and 0.41 for owner-occupied units.

The transport literature mainly focuses on the income-elasticity of the value of time. Unlike what Glaeser et al. (2008) assume, the income elasticity of the value of in-vehicle time has been documented to be close to 0.5 (see e.g. Shires and De Jong, 2009; Small et al., 2007, for two general reviews). Moreover, as discussed in Duranton and Puga (2014), the monetary cost of commuting is arguably non-negligible, and accounting for it drives down the income-elasticity of transport costs below 1. Using a structural model of modal choice estimated on British data, Van Ommeren and Dargay (2006) finds that monetary costs account for 14% of total commuting costs for an average commuter. Combining these elements, one cannot rule out a value of the income-elasticity of commuting costs significantly below 1.

Overall, given the existing literature, it appears difficult to conclude on the predictive power of the AMM model in terms of income sorting. In chapter 3, we revisit the income-elasticity criterion. By using an empirically-relevant form for the utility function, we show that the income-elasticity of housing demand has no reason to be constant, nor between cities nor within a city. Under these conditions, the predictions of the model are modified and relate better to observed city structures (see chapter 3).

The AMM model represents a simple representation of a city, which so far had ambiguous predictions. Urban economists have proposed many adaptations or extensions to this model, that reflect different mechanisms driving income sorting.

### 2.4.3 Refining accessibility

The AMM model describes a monocentric city, with a radial cost of commuting that is usually simplistic. In particular, the functional form for commuting costs usually leads to a constant income-elasticity. Providing finer representation of commuting costs yields richer results. In practice, urban commuters use both public and private transportation.

## 2.4. What drives income sorting in cities?

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As a first order approximation, public transit is slower, but private cars have a higher fixed cost. Therefore, high-income commuters favor cars, and low-income ones public transit. Moreover, public transit has a comparative advantage over cars for short commutes. Therefore, introducing two modes makes the poor more likely to live in inner cities. LeRoy and Sonstelie (1983) argue that the introduction of automobile as a more rapid mode led to the suburbanization of high-income inhabitants in the post-war era in the US. More recently, Glaeser et al. (2008) find that public transportation accessibility contributes to explain why low-income workers live in central US cities. Note that this approach relies on a variation of the Alonso-Mills condition, with an income-elasticity of transport costs that varies with income. They further argue that the availability of public transit is not uniform within cities nor between cities, which may explain the differences between “old” and “new” cities.

Note that we discuss more extensively the relationship between public transit, and more generally accessibility, and income sorting in chapter 4.

### 2.4.4 Amenities

Previous models only include the trade-off between accessibility to employment and land availability. We now turn our attention to models that incorporate other urban features, in particular that relax the “uniform land” assumption of the AMM model. In a seminal paper, Brueckner et al. (1999) assumes that inhabitants value both accessibility and local amenities. They differentiate “historical”, “natural” and “endogenous” amenities. The key assumption of their model is that the marginal valuation of amenities increases with income. Therefore, richer inhabitants tend to live in neighborhoods with higher amenities. The appeal of this theory is that it enables a city’s internal social structure to be linked to its idiosyncratic features. This theory is therefore compatible with the observed diversity of urban structures. In particular, Brueckner et al. (1999) illustrate their model with the differences between Detroit and Paris. The remarkable historical amenities of downtown Paris explain why SES is a decreasing function of distance in Paris (as illustrated on figure 2.1).

There is strong empirical evidence that supports this theory. For example, Koster et al. (2014) find that high-income households sort themselves in historical areas of Dutch cities. Lee and Lin (2017) highlight the role of natural amenities: they show that high-income households are attracted by neighborhoods with high-level of natural amenities such as ocean, lakes, mountains or hills, and that “high-amenities” cities show more persistence in their social structures over time. One of the interesting features of this model is that it allows for non-radial patterns. For instance, many European cities such as Paris have an East-West polarization. Heblich et al. (2021) show that it may be linked to historical pollution and dominant wind directions (for British cities).

Brueckner et al. (1999) also discuss a model of city with endogenous amenities, that is, amenities that depend on the composition of local population. They include, for

## 2.4. What drives income sorting in cities?

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instance, restaurants, shops and cultural equipment. They introduce greater complexity, as multiple equilibria can emerge in this framework. Dynamic versions with endogenous amenities show patterns of self-reinforcing dynamics. O’Sullivan (2005) embed an effect of the composition of the population on the levels of crime and the prices of local goods in an urban location choice model. As the share of high-income inhabitants increase in a neighborhood, crime decreases and local goods (e.g. shops, restaurants, bars) become more expensive, further attracting more high-income inhabitants. Some models, such as Guerrieri et al. (2013), directly include the proximity to other inhabitants of the same group as a determinant of location choice, in a manner that recalls the segregation model of Schelling (1971).

Closely related to the idea of endogenous amenities is the notion of local public good from Tiebout (1956). Inhabitants may “vote with their feet”, that is sort themselves into locations with their desired level of social policies. de Bartolome and Ross (2003) include local public expenditures in a monocentric model. In this context, inhabitants trade between accessibility, availability of land and the level of public goods. In order to remain tractable, their model includes two zones only: inner city and suburbs; and two income groups. One key features of their model is that there can be equilibria with income mixing. An example of local public good is air quality. Banzhaf and Walsh (2008) show that mean relative income increases in locations that experienced a decrease in air pollution in the US between 1990 and 2000.

### 2.4.5 Depreciation of the built stock and reinvestment

We finally mention supply-side models of income sorting, where the condition of the housing stock in each location drives the location of inhabitants. The filtering process, formalized by Sweeney (1974), assumes that as housing deteriorates over time, it is passed down to lower-income inhabitants, as high-income inhabitants favor renovated dwellings. Smith (1979) develops the “rent gap” theory. He states that as housing deteriorates, a gap between the actual value of housing and the shadow price for *renovated* housing grows. If this gap becomes sufficiently large, it becomes profitable for developers to invest and build (or renovate) housing and thus attract higher-income residents.

With a similar intuition, Brueckner and Rosenthal (2009) formalize a spatial urban model with filtering of housing. They assume that high-income inhabitants favor younger housing and that neighborhoods experience cycles of deterioration/renovation over time. Interestingly, this model links the spatial pattern of a city to its history. “Young” US cities have new homes in their outskirts and old housing in the center. “Older” cities may have renovated, thus rich, centers, then old inner suburbs and young outer suburbs. As cities grow old, income sorting is organized by rings of distance from the center. Using data on US metropolitan areas, Brueckner and Rosenthal (2009) show that the age of the housing stock is significantly correlated with income sorting.

The valuation of the age of housing depends on the maintenance and has arguably

## 2.5. What explains the gentrification of inner cities?

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a cultural component. In particular, whether this theory applies to European cities is questionable. European cities have a much older housing stock, and there is evidence that high-income inhabitants value the historical aspect (Koster et al., 2014). However, it may be adapted in the context of large-scale post-war construction of social housing. Such programs represented entire neighborhoods that deteriorated quickly over time and where a fast decline in socioeconomic status was observed (Van Beckhoven et al., 2009).

### 2.4.6 Cities in developing countries: formal and informal land use

Cities in the developing world face their own unique challenges that differentiate them from cities in developed countries (Brueckner and Lall, 2015). In particular, informal housing poses the specific question of new residents choosing simultaneously their location and their housing type.<sup>16</sup> Squatting of land is generally not possible everywhere and squatters may have a higher chance of being evicted on land where there is prospect of formal development (Turnbull, 2008). The timing of development may therefore be crucial, as noted by Brueckner and Lall (2015); Henderson et al. (2016).

On the contrary, eviction may be less frequent on land owned by public institutions (Shah, 2014) or on regulated or undevelopable land. One could think, for instance, of the *favelas* in Rio de Janeiro, built on steep slopes subject to landslides (O’Hare and Barke, 2002). Informality may also emerge as a by-product of formal housing policy. For instance, the “backyarding” phenomenon, in South African cities, is conditioned to the presence of public housing that were built as part of the Reconstruction and Development Plan (RDP) and Breaking New Ground (BNG) programs (Lemanski, 2009).<sup>17</sup> Such patterns are linked to city-specific natural, institutional or historical characteristics; and may be strong forces driving the income sorting.

## 2.5 What explains the gentrification of inner cities?

As described in section 2.3.3, central areas of large US cities, as well as large cities elsewhere, have seen an increase in relative socioeconomic status. Do the aforementioned theories explain this trend?

Early in the academic literature about gentrification, authors distinguished supply-side and demand-side explanations (Ley, 1986; Smith, 1979; Hamnett, 1991). On the supply side, the depreciation and reinvestment in housing structures explain how the dynamics in a neighborhood may reverse over time, as in the models of Smith (1979)

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<sup>16</sup>Selod and Tobin (2018) introduce a “tenure security” choice, arguing that the dichotomy between security and insecurity is actually a continuum of tenure security.

<sup>17</sup>Brueckner et al. (2018) develop a spatial economic model of backyarding which predicts that locations with both public housing and high accessibility to employment are likely to have a high density of “backyarders”. We adapt this model for the model developed in chapter 5.

## 2.5. What explains the gentrification of inner cities?

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and Brueckner and Rosenthal (2009) presented above.<sup>18</sup> However, investment in deteriorated housing may not be a sufficient condition for gentrification, as all low-income deteriorated neighborhoods have not experienced gentrification. There are examples of large scale urban renewal programs that had little impact on the residential composition of neighborhoods (see e.g. Chareyron et al., 2020). Moreover, the “rent gap” can only exist if high-income residents have a higher willingness-to-pay for the location than low-income ones. Therefore, urban economists have also explored demand-side explanations to gentrification. Such explanation can provide explanations to why high-income residents gradually outbid low-income ones in gentrifying neighborhoods, a phenomenon that has been recently documented in the case of the UK (Waights, 2018).

At first sight, the theories based on accessibility to employment appear limited. Transportation systems did not experience large-scale changes over the last decades, compared to the earlier introduction of streetcars in the late 19<sup>th</sup> century (Gin and Sonstelie, 1992) and the automobiles in the post-war period (Mieszkowski and Mills, 1993). The decentralization of low-skilled jobs, while high-skilled jobs remain concentrated, may entail changes in the relative accessibility as perceived by high- and low-income workers. Baum-Snow and Hartley (2015) test this assumption, but find limited evidence of a significant contribution to the 2000-2010 gentrification in US cities. Keeping job location and transportation systems constant, there may have been changes in individual’s valuation of commuting. Edlund et al. (2015) argue that the longer hours worked by high-income households increased their valuation of leisure time, thus increasing their opportunity costs of commuting and leading to a higher demand for central-city locations. Similar conclusions are reached by van Vuuren (2018), that argue than young college graduates value proximity to jobs as it facilitates social interactions and job search.

Reversal of dynamics within the “amenity” model can be due to (i) changes in local amenities or (ii) changes in preferences for amenities. Recent empirical evidence for US cities appear to support the assumption of changes in preferences, or “taste-driven” gentrification, a term coined by Kern (1981). Couture and Handbury (2017) study the predictors of location choices for young college graduates in US metropolitan areas over the period 2000-2010, and conclude that their change of taste for downtown amenities, such as restaurants or cultural equipment, is the most compelling explanation for gentrification.

Although recent empirical work for US cities appear to support “cultural” explanations of gentrification (see the review by Hwang and Lin, 2016), gentrification may also be linked to metropolitan-level supply and demand. Two papers study this question. First, Guerrieri et al. (2013) derive a model in which gentrification emerges through neighborhood effects: when a housing demand shock occurs, the neighborhoods close to rich neighborhoods gentrify, and as a result housing prices increase. Second, Gyourko

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<sup>18</sup>Both models were explicitly developed to provide explanations for recent trends of inner-city gentrification.

## 2.6. Conclusion

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### Frame 2.3: The consequences of gentrification

Is gentrification good, or bad? This question remains vastly open (Hyra, 2016) and has been at the center of a rather controversial debate (Byrne, 2002; Newman and Wyly, 2006). Vigdor et al. (2002) provide a relevant decomposition of the different questions one should tackle in order to answer it. On the one hand, because of gentrification, low-income residents may be “displaced” from the central areas of large cities, where they benefited from access to public transit, central-city amenities, public services and, perhaps most importantly, economic opportunities. As they move to remote suburban locations, they may lose access to these features of central areas, or suffer from long and potentially costly commutes. Couture et al. (2018) recently made this point about inner-city gentrification in the US. Using a spatial equilibrium model, they show that income growth at the top of the income distribution led to inner city gentrification, which made the low-skilled resi-

dents worse off. On the other hand, some authors have argued that the potential positive effects of gentrification are often neglected, in particular regarding tax revenues and economic activity (Byrne, 2002).

A question that has, to our knowledge, never been treated is whether remoteness of low-income residents from jobs and public services may also increase vulnerability to variations in fuel prices. This may contribute to explain the resentment against the fuel tax that was expressed by the “*Yellow Vests*” in France in 2018. In Paris, workers from low-income occupational categories live significantly further from the center of the agglomeration in 2010 than they did in 1968 (see chapter 4). Many authors have documented the growing differences between large cities and “peripheral” areas in France (see e.g. Guilluy, 2018), however it appears that none has linked this to the recent trend of gentrification ongoing in metropolitan areas.

et al. (2013) argue that inelasticity of housing supply can lead to crowding of low-income inhabitants from desirable places when a shock on demand occurs at the national level. Both papers link national or metropolitan level evolution in demand for housing to local gentrification. However, both models do not explain why gentrification is concentrated specifically in the central areas of large cities.

## 2.6 Conclusion

Urban economics theory has been particularly successful in explaining some spatial patterns in cities, such as the negative “density gradient” that is observed in very different contexts (see e.g. Bertaud and Malpezzi, 2003). This is not the case with patterns of

## 2.6. Conclusion

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location by income. In this chapter, we presented some stylized facts and showed that spatial patterns vary across cities and change over time in non-systematic ways. These facts make it difficult to come up with a theoretical model that is empirically relevant in all situations. As an example, we presented the recent trend of inner-city gentrification, and discussed how recent contributions (focusing mostly on US metropolitan areas) have linked this trend with many potential factors.

*Overall, income sorting appears to be the result of multiple forces.* For a modeling objective, it is clear that the aforementioned potential drivers of income sorting cannot *all* be incorporated in a simulation model. Therefore, the modeler has to choose which mechanisms to include. This choice can be made based on two criteria: (i) on the assumption that some mechanisms are of first-order importance, while others are secondary, or (ii) based on the objective of the simulation exercise.

This choice is obviously not specific to models of income sorting. However, given the high number of relevant theories, option (ii) has a particular appeal in the case of income sorting. The choice of the mechanisms to include in a model of income sorting should be driven first by the purpose of the simulations. For instance, if the simulations aim at assessing transport policies (as in chapter 4), a significant effort should be put to the modeling of income-related accessibility mechanisms.

Another takeaway from this literature review is that a model built on a handful of mechanisms is unlikely to reproduce the empirical spatial patterns of income sorting. In order to fit to reality, recent quantitative urban models all incorporate idiosyncratic neighborhood-specific and/or group-specific parameters (see e.g. Anas and Liu, 2007; Ahlfeldt et al., 2015; Tsivanidis, 2018, and the discussion in chapter 1). Idiosyncratic parameters compensate for the fact that the underlying theoretical models are not capable of reproducing the observed spatial patterns.<sup>19</sup> They enable the model to fit to the reality. The introduction of such “idiosyncratic” parameters is justified by the theories that link observed patterns with idiosyncratic features of cities and neighborhoods (history, amenities), or idiosyncratic tastes of specific groups.

These two conclusions are used in the models of chapters 4 and 5. In both models, we introduce two elements: (i) some specific mechanisms that we believe are important *given the research questions*, and (ii) idiosyncratic parameters, that enable the models to fit the reality in the initial situation and to run simulations “all else equal”.

Apart from the modeling-oriented conclusion, we take away two messages from the gentrification of inner-city neighborhoods. First, identifying global trends among the complexity remains an important objective for research. The trend of inner-city gentrification appears to be common to several large metropolitan areas (if not all above a certain population), and further research could seek to provide a cross-country system-

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<sup>19</sup>Note that quantitative models with a representative agent do not always exhibit such parameters (see e.g. Vigi   and Hallegatte, 2012). One reason may be that, as mentioned above, the standard urban model with a representative agent is able to reproduce well the most salient features of real cities (negative rent and density gradients).

## 2.6. Conclusion

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atic review, that does not exist to our knowledge. Second, multiple explanations have been proposed in the literature, as discussed in section 2.5. In chapter 3, we present how the standard income-elasticity criteria, presented in section 2.4, can provide another explanation to this phenomenon, when applied under realistic assumptions.



## Chapter 3

# Inner-city gentrification in a monocentric urban model<sup>1</sup>

*The late 20th century was the age of poor inner cities and wealthy suburbs; the 21st century is emerging as an age of affluent inner neighborhoods and immigrants settling on the outside.*

Alan Ehrenhalt, *The Great Inversion*

### 3.1 Introduction

We discussed in chapter 2 that different cities have different patterns of location by income. A common view about cities in the United States (US) is that the poor residents live in the center while the rich live in the suburbs. This view, however, does not apply to every city. For instance, income is higher in Manhattan than is the rest of New York City.<sup>2</sup> We also discussed the fact that patterns change over time. For instance, Socioeconomic Status (SES) decreased in central cities as a result of the “urban flight” in the post-war era. Over the last two decades, the SES of central areas in large US cities increased as part of the process of gentrification.

In this chapter, we present a novel mechanism of location by income. Understanding why patterns differ between cities, as well as what drives the changes over time, is an important objective for research. The causes of the recent trends of gentrification and the “suburbanization of poverty” in large cities have not yet been fully identified, and in particular the role of metropolitan-level supply and demand for housing.<sup>3</sup>

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<sup>1</sup>This chapter is adapted from an article co-authored with Vincent Vigi e, and Franck Lecocq. A first version has been published as a CIRED Working Paper under the title "Could City Population and Containment Favor Gentrification?"

<sup>2</sup>According to the American Community Survey, in 2016, the median annual income in New York County, NY, which encompasses Manhattan island, was 75,513\$. In comparison, the median income for the Urbanized Area (UA) of "New York-Newark" was 68,319\$.

<sup>3</sup>See the discussions in chapter 2 and in Hwang and Lin (2016).

### 3.1. Introduction

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As presented in chapter 2, the Alonso-Muth-Mills (AMM) model is a tool to represent the equilibrium supply and demand for housing in a city. It also provides insights on the location choices as a function of income. This model has a simple criterion for determining the city structure: poor inhabitants live in the center if the income-elasticity of transport costs is higher than the income-elasticity of housing demand. In the general case, this criteria is not able to explain why urban structures vary between cities (Brueckner et al., 1999), and how patterns can change over time.

In this chapter, we introduce a realistic specification for housing demand in a monocentric model, and show that this leads to novel results both in terms of housing expenditures and city structure. We consider a Stone-Geary utility function, that captures the fact that housing is a *necessity good*.<sup>4</sup> Alternatively, this utility function also captures the fact that household have a basic need in housing.

Introducing this change leads to an income elasticity of housing demand that depends on the level of rents. Therefore, the functioning of the model is as follows: in small cities, low-income residents have a preference for the center because they have a relatively higher transport cost. However, housing is more expensive in large cities than in small ones. In the center of large cities, housing prices may be too high for low-income residents to meet their basic need in housing towards the center. In this case, they favor suburban locations where they can meet their housing needs. In other terms, it may be impossible for low-income households to live in a decent apartment in the center of a large city. We document that the structure of US cities are consistent with these predictions: small and medium cities have relatively poorer centers and richer suburbs, with large metropolitan areas have richer centers, poorer inner suburbs and richer outer suburbs.

Because of the basic need in housing, housing expenditures varies with income but also with local level in rents. Urban equilibrium implies that housing expenditures will be higher, all else equal, in cities with large population, or with more constrained land use. Using American Community Survey microdata, we show that these predictions are consistent with housing expenditures of US households. This suggests unequal “costs of agglomeration”, as discussed in chapter 1.

The main conclusion we derive from this chapter is that a monocentric model with a realistic representation of housing demand yields two different city structures: small cities have poor centers and rich suburbs, while large cities have rich centers, poor inner suburbs and rich outer suburbs. As cities grow, they become more likely to shift from the first structure to the second. We show that this prediction of our models is consistent with observations on US cities.

This chapter mainly contributes to the literature on the monocentric model of cities and the literature on income sorting within cities, reviewed in chapter 2. This chapter also relates to the literature on the structure of housing demand. A robust result from

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<sup>4</sup>A necessity good is a good for which the share of budget decreases with income, or equivalently a good for which both the income elasticity and price elasticity of demand are below 1.

## 3.2. Model

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the literature on housing demand is that housing is a “necessity good” meaning that low-income households devote a higher share of their budget to housing than high-income households do. Accordingly, most studies find an income-elasticity of demand for housing below 1 for the US housing market (De Leeuw, 1971; Mayo, 1981; Goodman, 1988; Albouy et al., 2014; Rosenthal, 2014). These estimates of income-elasticity of housing demand assume that it is constant across locations. However, as noted by Mayo (1981), if housing is a necessity good, then the income-elasticity of housing demand should vary negatively with housing prices, and positively with income.<sup>5</sup>

This chapter also relates to recent papers introducing Stone-Geary specifications in urban land models. Tsivanidis (2018) and Gaigne et al. (2020) introduce Stone-Geary specification for housing demand in quantitative urban models. However, they do not discuss the theoretical implications of this utility function specification for the income-elasticity criteria.

Rest of the paper is organised as follows: section 4.4 presents our model and shows that two city configurations may exist. We compare the theoretical predictions of the model with empirical observations on US cities in section 3.3. Finally, section 4.10 concludes the paper.

## 3.2 Model

Our model builds on a standard Alonso-Muth-Mills (AMM) model, as presented in Fujita (1989), to which we introduce the Stone-Geary utility specification. The major difficulty with this specification is proving the uniqueness of the spatial equilibrium. We provide a proof in the case of two income groups, under simplifying assumptions.

Let us consider a one-dimensional city with all jobs in a central business district (CBD) located in  $x = 0$  (monocentric city).<sup>6</sup> Households located at distance  $x$  from the center pay a transport cost  $T(x)$ . Locations are only differentiated by transport costs and the quantity of available land  $\mu(x)$ .

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<sup>5</sup>Rosenthal (2014) estimates an income-elasticity of housing demand of 0.124 for rented units and 0.41 for owner-occupied units. The differences between the two values may suggest that rents and owners do not have the same behavior on the housing market. Another assumption is that renters are on average poorer than owners, and therefore, in line with Mayo (1981), have a lower income-elasticity.

<sup>6</sup>The monocentric assumption is highly simplistic, but it enables greater tractability of the theoretical model. Note that our model could be adapted to a polycentric framework, for instance by replacing the linear commuting cost by a two-dimensional accessibility score (see e.g. Gaigne et al., 2020). Its message would remain that in expensive cities, basic needs in land consumption would invert the income sorting resulting from the accessibility/space trade-off in the locations with the best accessibility to job.

## 3.2. Model

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### 3.2.1 Household demand

Households derive utility from the consumption of land<sup>7</sup>  $q$  and a composite good  $z$ . Their utility is a Stone-Geary function:

$$U(z, q) = z^{1-\alpha}(q - q_0)^\alpha \quad (3.1)$$

where  $0 < \alpha < 1$ , and  $q_0 > 0$  represents the minimum amount of land that households consume, bearing in mind that land parcels cannot be arbitrarily small, as a house must have basic utilities and a minimum living space<sup>8</sup>.

The budget constraint is:

$$Y = q \cdot R(x) + z + T(x)$$

with the price of the composite goods being set to 1 and  $R(x)$  being the land rent at location  $x$ . Maximizing utility under budget constraint leads to the linear expenditure system:

$$\begin{cases} (q - q_0)R & = \alpha(Y - T - q_0R) \\ z & = (1 - \alpha)(Y - T - q_0R) \end{cases} \quad (3.2)$$

According to this utility specification, the consumer spends a committed amount on land  $q_0$  and then divides the remaining budget between the consumption of land and composite good in fixed proportions. From equation 4.2, we can also derive the housing expenditure:

$$qR = \alpha(Y - T) + (1 - \alpha)q_0R \quad (3.3)$$

Under a Cobb-Douglas utility function ( $q_0 = 0$ ), for a given transportation cost  $T$ , the housing expenditure is an affine function of income. Where  $T = 0$ , it is a fixed share  $\alpha$  of income. With a Stone-Geary specification, for a given  $T$  the housing expenditure depends on the rent  $R$ . Therefore, the share of income spent on land increases with the rent. Moreover, for given  $T$  and  $R$ , the share of income spent on housing is lower for richer households.

### 3.2.2 Bid rent slopes

Let us define  $\Psi(u, x)$  as households' bid rent, i.e., the maximum rent that households bid at location  $x$  in order to attain utility  $u$ , and  $Q(u, x)$  as the bid-max lot-size, the corresponding land consumption.

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<sup>7</sup>It does not affect the model to assume that  $q$  is a consumption of land and  $\mu$  (see below) a supply of land, or to suppose that  $q$  is a consumption of housing and  $\mu$  an exogenous supply of housing.

<sup>8</sup>We do not introduce a minimum amount of consumption of the composite good. Because the price of the composite is normalized to 1, introducing a non-null  $z_0$  would be equivalent to reducing the household income by  $z_0$ . An underlying assumption of our utility function is that by difference, the composite good is a luxury good.

### 3.2. Model

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Following Fujita (1989), the slope of the bid-rent is:

$$\frac{\partial \Psi}{\partial x} = -\frac{T'(x)}{Q(u, x)} \quad (3.4)$$

In the monocentric model, the relative location of residents according to their income is determined by whether the slope of the bid-rent gets steeper, or flatter, as income increases. A well-known result of urban theory is that this condition implies that the rich live on the outer ring of the city, and the poor in the center, if the income elasticity of marginal transport cost  $\epsilon_{T',Y}$  is less than the income elasticity of lot size  $\epsilon_{Q,Y}$  (Alonso, 1964; Fujita, 1989), that is:

$$\left(\frac{Y}{T'}\right) \left(\frac{\partial T'}{\partial Y}\right) < \left(\frac{Y}{Q}\right) \left(\frac{\partial Q}{\partial Y}\right) \quad (3.5)$$

We assume that transport cost  $T(x)$  includes a monetary cost ( $\tau_1 x$ ) and an opportunity cost of time proportional to income ( $\tau_2 Y x$ ), that is:  $T(x) = (\tau_1 + \tau_2 Y)x$

The income elasticity of transport cost is:

$$\epsilon_{T',Y} = \frac{\tau_2 Y}{\tau_1 + \tau_2 Y} \quad (3.6)$$

Under this specification, the income elasticity of transport cost is always between 0 (the limit case where the only cost is the monetary cost) and 1 (the limit case where the monetary cost is null).

The income elasticity of lot size is:

$$\epsilon_{Q,Y} = \frac{1 - \tau_2 x}{1 - \left(\frac{\tau_1}{Y} + \tau_2\right)x + Rq_0 \left(\frac{1-\alpha}{\alpha Y}\right)} \quad (3.7)$$

Note that if  $q_0$  is zero, i.e. in the case of a Cobb-Douglas utility function, the income elasticity of lot size is larger than one. In this case, we always have  $\epsilon_{T',Y} < \epsilon_{Q,Y}$ , and the poorer residents live near the center.

In the Stone-Geary case, the term  $Rq_0(1-\alpha)/(\alpha Y)$  that drives down the elasticity. This term depends on the value of local rent  $R$ . Because, of this term, the income elasticity of lot size can be either superior or inferior to the income elasticity of marginal transport cost. A simple calculation leads to the following proposition:

**Proposition 1** (Bid rent slopes). *The income elasticity of marginal transport cost is lower than the income elasticity of lot size if and only if the rent  $R$  is below a limit value  $R_{lim}$ :*

$$\epsilon_{T',Y} < \epsilon_{Q,Y} \quad \Leftrightarrow \quad R < R_{lim} = \frac{\alpha \tau_1}{(1-\alpha)\tau_2 q_0} \quad (3.8)$$

Therefore, the sign of the derivative of the bid-rent slope according to income is inverted depending on whether  $R$  is superior or inferior to  $R_{lim}$ . Where rents are low compared to  $R_{lim}$ , bid lot sizes are large compared to the basic need  $q_0$ , the situation is

## 3.2. Model

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close to a situation with a Cobb-Douglas utility function. In this situation, rich households tend to locate on the outer part of the city. On the contrary, where rents are above  $R_{lim}$ , richer residents will locate toward the center. Note that limit rent  $R_{lim}$  above which this mechanism intervenes decreases with  $q_0$ .

The consequence of this proposition is that, contrary to the Cobb-Douglas case, there can be multiple crossing points between bid-rents.

### 3.2.3 City structure

We now consider a city population by  $N$  households divided in two groups:  $N_p$  *poor* households earning income  $Y_p$  and  $N_r$  *rich* earning  $Y_r$ , with  $Y_p < Y_r$ .

We further assume that the border of the city  $x_{max}$  is located where rents fall to 0<sup>9</sup>, that is:

$$R(x_{max}) = \max_{p,r} (\Psi_p(u, x_{max}), \Psi_r(u, x_{max})) = 0$$

Under these assumptions, we show that the city can only be in two configurations in terms of income sorting. Moreover, we define the equilibrium and show its uniqueness for a given set of parameters.<sup>10</sup> Formal proofs for these results are provided in Appendix 3.A.

**Proposition 2** (Two configurations). *There can only be two city configurations: one with low-income households in the center and high-income households in the periphery, the other with high-income households in the center and outer periphery, and low-income households in the inner periphery.*

*Proof.* See Appendix 3.A.2. □

Figure 3.1 illustrates the two possible configurations. When rents are low, i.e., when plot sizes for low-income households are large compared to  $q_0$ , the city structure is similar to figure 3.1a. The structure of figure 3.1b can only exist if rents in the center are above  $R_{lim}$ .

As detailed in Appendix 3.A.1, the basic need in lot size puts a maximum limit on city population. Therefore, in the closed-city case with more than one income group, the existence of the equilibrium given a set of parameter cannot be formally proven.<sup>11</sup> However, we show the following proposition:

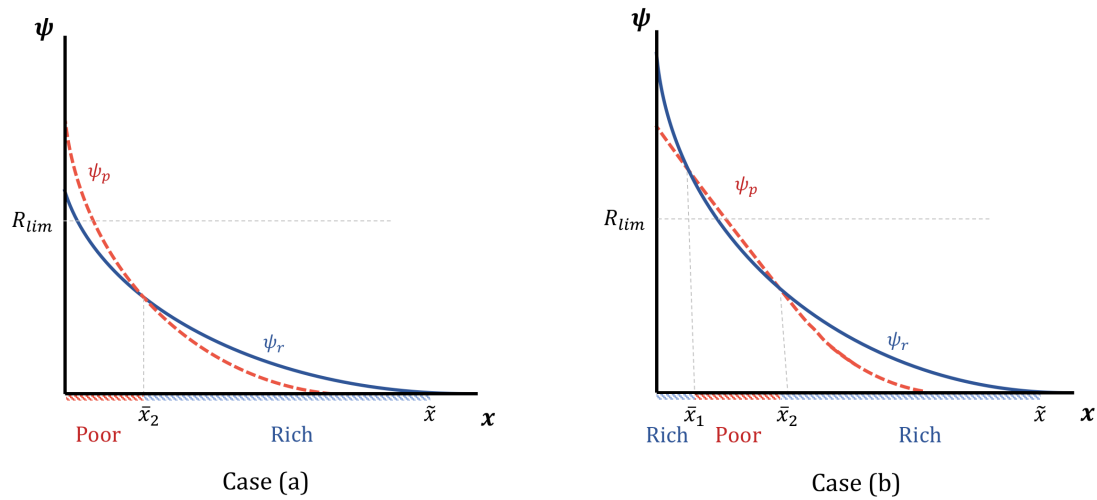
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<sup>9</sup>The main qualitative results of the paper would hold with an agricultural rent defining city limits. However, this would add complexity as specific cases may arise (for instance if the agricultural rent is above  $R_{lim}$ ). For simplicity, we consider here the specific case of a monocentric city with an agricultural rent equal to 0.

<sup>10</sup>Note that a Stone-Geary utility function is not “well-behaved” in the sense of Fujita (1989). Therefore, all the results from Fujita (1989) showing the existence and uniqueness of equilibrium with multiple household types do not hold in this context.

<sup>11</sup>Contrary to a Cobb-Douglas case, total population does not diverge towards  $+\infty$  when utility tends to 0. Therefore, if total populations ( $N_p, N_r$ ) are too large, the equilibrium may not exist.

### 3.2. Model



(a) Low-income in the center, high-income in the suburbs

(b) High-income in the center, low-income in the inner suburbs, high-income in the outer suburbs

Figure 3.1: Bid rent for high- and low-income households and the two possible configurations. Case (a) represents a *poor-rich* city, whereas in case (b) high-income households live in the center, low-income households in the inner periphery, and high-income households in outer periphery (*rich-poor-rich* city).

**Proposition 3** (Uniqueness of the equilibrium). *In the closed-city case with two income groups, if the equilibrium exists, then it is unique.*

*Proof.* See Appendix 3.A.3. □

#### 3.2.4 Comparative statics

We present here the main intuition behind comparative static analysis. For a formal discussion on these effects in the case of a city with two income groups, see Appendix 3.B.

**Effect of city population** In the closed-city case, a well-known result is that a city with a large population has higher rents in the center than a city with a smaller population, as the demand for residential land is higher (see Fujita, 1989, p.77 and p.124). Such a result also hold in our model, and has implications in terms of housing expenditures and income sorting. First, equation 3.3 predicts that in large cities, households will spend on average a higher share of their income on housing, all else equal. In small cities, rents are low, and poor residents live in the center, while rich ones live in the suburbs. However, beyond a specific threshold of city size, our model predicts that rich residents live in the center, while poor residents live in the inner suburbs. We show in Appendix 3.B.1 that, for a given set of parameter, we derive a sufficient condition under which, if

### 3.3. Empirical consistency of the main model predictions

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an equilibrium exists, it is in the *rich-poor-rich* configuration. An extension of this result to multiple income groups would provide the following result: beyond a threshold in size, cities exhibit a *U-shape* relationship between income and distance from the center.

**Effect of land supply** The effect of land supply is opposite to city population. Lower land supply  $\mu$  tend to increase prices in the equilibrium. Therefore, all else equal, households spend a higher share of their budget on housing in a city with a lower land availability. Moreover, land availability may alter the income sorting at the equilibrium.

**Effect of income inequality** The model also yields predictions on the effect of income distribution. Consider a city with a given set of parameters, in particular income  $Y_p$  for the poor and  $Y_r$  for the rich, for which an equilibrium exists in the *poor-rich* configuration. Keeping the income of the poor fixed  $Y_p$ , an increase in the income level of the rich  $Y_r$  leads to higher rents in the city, as their demand increases. Because of equation 3.3, this should cause an increase housing expenditures of the poor.<sup>12</sup> Moreover, as rent increases, it may cause the city to switch from a *poor-rich* to a *rich-poor-rich* configuration. We show in Appendix 3.B.3 that there is an income level  $Y_r$  above which the city is in the *rich-poor-rich* configuration. Through this mechanism, an divergence in income levels may lead to a change in the city structure.

**Effect of transport speed** The “speed” parameter  $\tau_2$  captures the valuation of the time spent per unit of distance from the center. As speed increases ( $\tau_2$  decreases), transport is less costly, the city is more sprawled out and rents in the center decrease. Moreover, as  $\tau_2$  decreases, the limit rent  $R_{lim}$  increases (see equation ). Therefore, bid-rents become flatter with income is more locations (see Appendix3.B.4 for more details). As a consequence, as  $\tau_2$  decreases, low-income residents occupy more central locations. Such a result could be applied to explain the changes in income sorting in US cities in the second half of the 20<sup>th</sup> century, as transport speed arguably increased in cities as a result of the generalization of a new technology (private car) and infrastructure investments (Mieszkowski and Mills, 1993; Baum-Snow, 2007). The model suggests that such a change should lead to the suburbanization of rich households and the emergence of the structure with poorer residents in the center and rich in the suburbs.

### 3.3 Empirical consistency of the main model predictions

We verify that the main predictions of the theoretical model are consistent with observations on US cities. More precisely, we consider the two main takeaways of the model, in terms of housing demand and city structures:

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<sup>12</sup>On the contrary, for a given  $Y_r$ , a decrease in  $Y_p$  should lead to decreasing housing expenditures for the rich.



### 3.3. Empirical consistency of the main model predictions

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1. Under the assumption of a Stone-Geary utility function, a household devotes a higher share of their income on housing as they are poorer. Moreover, all else equal, households are expected to have higher housing expenditures in cities with a large population, constrained land use, and when other inhabitants are relatively richer.
2. In small cities, residential income increases with distance from the center, while large cities display a *U-shape* relationship between income and distance from the center.

To do so, we use local data from the American Community Survey. We use the definition of Urban Area (UA) from the Census Bureau. Urban Areas are defined as an aggregation of Census Tracts with minimum population density requirements (based on the 2010 Census).

#### 3.3.1 Data sources

**Housing expenditures data** Households' housing expense information is available in the Public Use Microdata Sample (PUMS) of the Census Bureau's American Community Survey (ACS), for the year 2016. We use primarily the household-level table, and we add commuting information extracted from the person-level table.

The lowest geographical level where household location is geo-coded is the Public Use Microdata Area (PUMA) level. Using GIS tools, we link each PUMA to an UA by considering the UA with the largest intersection area.

**Neighborhood composition data** In order to describe the internal structure of cities, we use the ACS aggregate results at the Census Tract level, in 2010 and 2016. The variables include the tract population, the median tract income and the share of college graduates among the population aged 25-64.

**Other data sources** For each UA, we use Origin-Destination Employment Statistics of the 2014 Longitudinal Employer-Household Dynamics (LEDH) data to define each UA's center ("CBD"). For every tract, we compute the average employment density for the tract and its adjacent ones. The CBD is the centroid of the tract with the highest corresponding average job density in the UA.

Following Saiz (2010), we consider that natural constraints are a key determinant of the level of housing prices/rents in an urban area. We compute the proportion of land in a radius of 30 km around the center that is not developable due to water or steep slopes. To do so, we use hydrological (National Hydrography Dataset) and topographic (Global Multi-resolution Terrain Elevation Data 2010) data from USGS databases.

### 3.3. Empirical consistency of the main model predictions

#### 3.3.2 Housing expenditures

Figure 3.2 presents the average share of income spent on housing as a function of income, for owners (owner costs) and renters (gross rent). The share of budget devoted to housing appears to sharply decrease with income. This aggregate result may be the result of unobserved factors, in particular the location, the household type, or the length of occupancy of the dwelling. Because owners free of mortgage or loan payments spend a significantly lower share of their budget, we remove them from for the rest of the analysis.

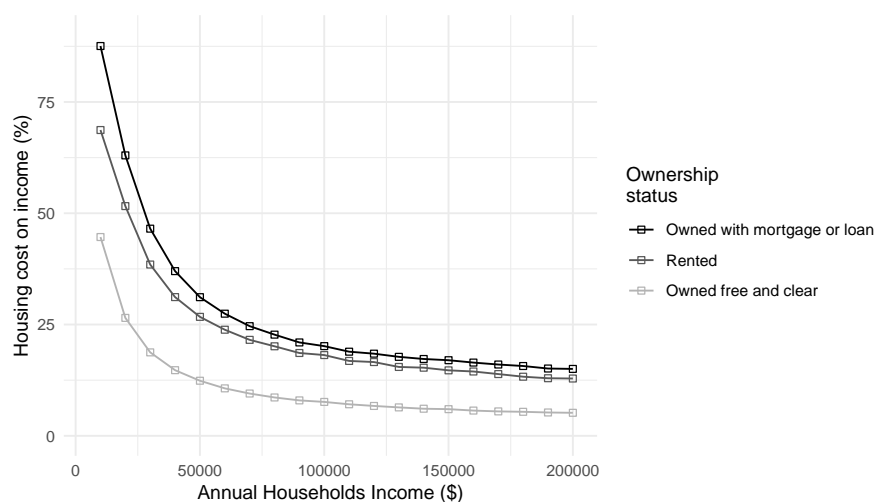


Figure 3.2: Average share of budget spent on housing as a function of income. Budget spent on housing represents the gross rent for renters, owner costs for owners. Shares were averaged by intervals of 10k\$. Source: American Community Survey 2016.

In columns (1) and (2) of table 3.1, we regress the housing expenditure as a share of income on the annual household income. We control by location by adding PUMA fixed effects and commuting variables. Commuting variables include the total travel time to employment for the household by car, the total time by public transit, the total time by walking and bicycle, and the number of commuters in the households. We also control by family composition (family and employment status variable, and number of children), tenure status, the year the household moved in the current dwelling, and the type of heating (as heating may be included in the rent). In column (1), the equation is linear, while in column (2) it is log-linear.

In columns (3)-(7), we present the result of regressions based on equation 3.3. We include UA-level variables that capture the average price in a city. UA-level variables include the total population, the share of land constrained for urban development, and variables describing the income distribution. We also control for the same household-level variables as for columns (1) and (2).

Results of columns (1) and (2) confirm that the share of income devoted to housing decrease with income, as shown on figure 3.2. High-income households spend a lower

### 3.3. Empirical consistency of the main model predictions

Table 3.1: Housing expenditures regressions

|                             | <i>Dependent variable:</i>     |                      |                        |                            |                        |                       |                       |
|-----------------------------|--------------------------------|----------------------|------------------------|----------------------------|------------------------|-----------------------|-----------------------|
|                             | Housing expenditures on income |                      |                        | Housing expenditures (k\$) |                        |                       |                       |
|                             | <i>linear</i>                  | <i>log</i>           |                        |                            | <i>linear</i>          |                       |                       |
|                             | (1)                            | (2)                  | (3)                    | (4)                        | (5)                    | (6)                   | (7)                   |
| Household income            | -0.093***<br>(0.0003)          |                      | 0.063***<br>(0.0001)   | 0.317***<br>(0.002)        | 0.347***<br>(0.002)    | 0.046***<br>(0.0002)  | 0.053***<br>(0.0002)  |
| Household income (log)      |                                | -0.598***<br>(0.001) |                        |                            |                        |                       |                       |
| UA population               |                                |                      | 0.0003***<br>(0.00000) | 0.0001***<br>(0.00000)     | 0.0001***<br>(0.00000) | 0.001***<br>(0.00001) | 0.001***<br>(0.00001) |
| UA constrained land (%)     |                                |                      | 0.070***<br>(0.001)    | 0.026***<br>(0.001)        | 0.030***<br>(0.001)    | 0.089***<br>(0.002)   | 0.093***<br>(0.002)   |
| UA Gini                     |                                |                      |                        |                            | 2.677***<br>(0.852)    |                       | -1.859<br>(1.386)     |
| UA 3rd quartile income      |                                |                      |                        | 0.034***<br>(0.001)        |                        |                       |                       |
| UA 1st quartile income      |                                |                      |                        |                            |                        | 0.457***<br>(0.004)   |                       |
| PUMA fixed effects          | x                              | x                    |                        |                            |                        |                       |                       |
| Commuting controls          | x                              | x                    | x                      | x                          | x                      | x                     | x                     |
| Tenure status control       | x                              | x                    | x                      | x                          | x                      | x                     | x                     |
| Family composition controls | x                              | x                    | x                      | x                          | x                      | x                     | x                     |
| Year moved controls         | x                              | x                    | x                      | x                          | x                      | x                     | x                     |
| Heating fuel controls       | x                              | x                    | x                      | x                          | x                      | x                     | x                     |
| Sample                      | All households                 |                      | UA bottom 25% earners  |                            | UA top 25% earners     |                       |                       |
| Observations                | 509,925                        | 509,925              | 509,925                | 71,787                     | 71,787                 | 183,327               | 183,327               |
| R <sup>2</sup>              | 0.319                          | 0.606                | 0.442                  | 0.449                      | 0.437                  | 0.402                 | 0.363                 |
| Adjusted R <sup>2</sup>     | 0.317                          | 0.605                | 0.442                  | 0.449                      | 0.436                  | 0.402                 | 0.363                 |

Sample is the ACS PUMS data of 2016, restricted to Urban Areas above 50k inhabitants, and to households who rent their dwelling, or owners with mortgage or loan. Commuting controls include the total travel time to work by car, by public transport and by walking for the household, as well as the number of commuters. Tenure status control is a dummy variable for a renter (ref. owner with mortgage or loan). Household composition controls include a set of dummy variables for family and employment status, as well as for the number of children in the households. Year moved controls are a set of dummy variables for the year the household moved in their current dwelling. Heating fuel controls are a set of dummy variables for the type of fuel used for heating. Regressions are weighted by the ACS household weights. *Note:* standard errors in parenthesis; \*p<0.1; \*\*p<0.05; \*\*\*p<0.01

### 3.3. Empirical consistency of the main model predictions

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share of their income on housing, even when controlling for family composition, tenure status, commuting modes and times, the year the household moved in, heating fuel of the dwelling, and location (at the PUMA level). This suggests that income is a *necessity good*. This result is not novel, as previous studies have reached comparable conclusions in the case of the US (De Leeuw, 1971; Mayo, 1981; Goodman, 1988; Albouy et al., 2014).

Columns (3) suggests that households living in larger cities, and cities with more constrained land use, have higher housing expenditures. This is consistent with the predictions of our model. Cities with larger population and more constrained land have higher housing prices, which results in higher housing expenditures because of the  $q_0$  term in equation 3.3. Results of table 3.1 suggest that a city with 100k more inhabitants is associated with annual housing expenditures that are 30\$ higher. Similarly, a city with a share of constrained land that is 1 pp. higher is associated with 70\$ more in annual expenditures on housing.

In columns (4) and (5), we restrict the sample to the first quartile of earners in each UA, and to the top quartile in columns (6) and (7). Results suggest that households in the bottom 25% spend more on housing if the Gini coefficient is larger. On the contrary, households in the top quartile appear unaffected (negative coefficient with large uncertainty) by an increase in the UA Gini coefficient. This is in line with our theoretical results: all else equal, high-income households are expected to spend less on housing if low-income residents are poorer. On the contrary, if the 1st quartile of income is higher, they spend more (consistently with the result of column 6 of table 3.1).

#### 3.3.3 City structure

In order to compare the structure of US cities, we follow Hwang and Lin (2016) and build a Socioeconomic Status (SES) index, that captures the relative rank of a Census Tract within the urban area. We define the SES Index of a census tract is the percentile rank, within the UA, of the average between (i) its rank in share of college graduates among population aged between 25 and 64 years and (ii) its rank in median households income. This index ranks between 0 (low status) and 1 (high status).

On figure 3.3, we display the average SES index for rings of distance to the UA center. The distance is expressed as cumulative total population. The figure shows that, in the largest US cities (with a population above 5M), the SES of households follows a U-shaped curve as a function of distance to the city center, whereas in smaller cities SES is on average the lowest in the central areas. As presented in Appendix 3.D, this result is robust when considering only the income, or only the share of college educated.

The structure of US cities, with low-income living in the center, is a well-documented fact (Brueckner et al., 1999). Figure 3.3 shows that this structure is indeed the “average” structure, except for the largest metropolitan areas, which have a non-monotonic relationship between income and distance from the center. The U-shape structure of large cities is in line with the predictions of the theoretical model. It has also be noted by

### 3.3. Empirical consistency of the main model predictions

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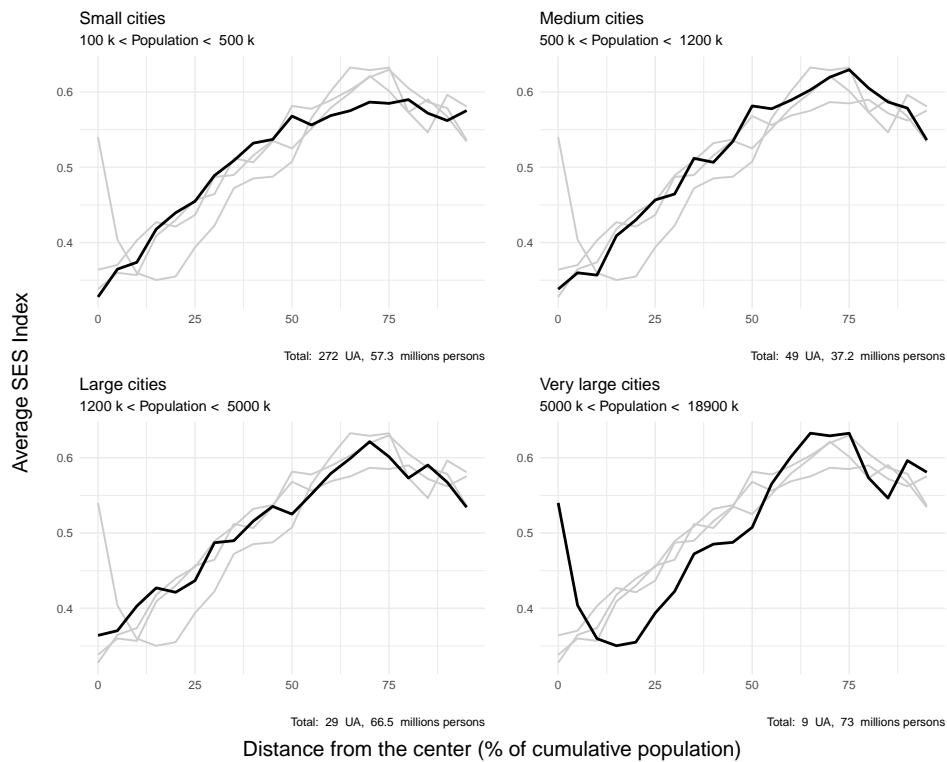


Figure 3.3: Average Socioeconomic Status (SES) Index of Census Tracts as a function of distance to the center for cities with different total populations in 2016. Distance is expressed as the cumulative share of tract population in 2016. Source: American Community Survey 2016.

### 3.4. Conclusion

Glaeser et al. (2008) in the US, and by Floch (2014) in the case of France.

Figure 3.4 is similar to figure 3.3, but presents the evolution of average SES index between 2010 and 2016. In large cities, the socioeconomic status in central area grew relatively more than in suburban locations. Central-city tracts of cities with population above 5 millions inhabitants changed quickly, as they gained on average 0.5 points in SES index within 6 years. Such a pattern exists but is less pronounced for medium cities. On the contrary, cities between 100,000 and 500,000 inhabitants present an inverted dynamic, as the average SES index decreases in the center.

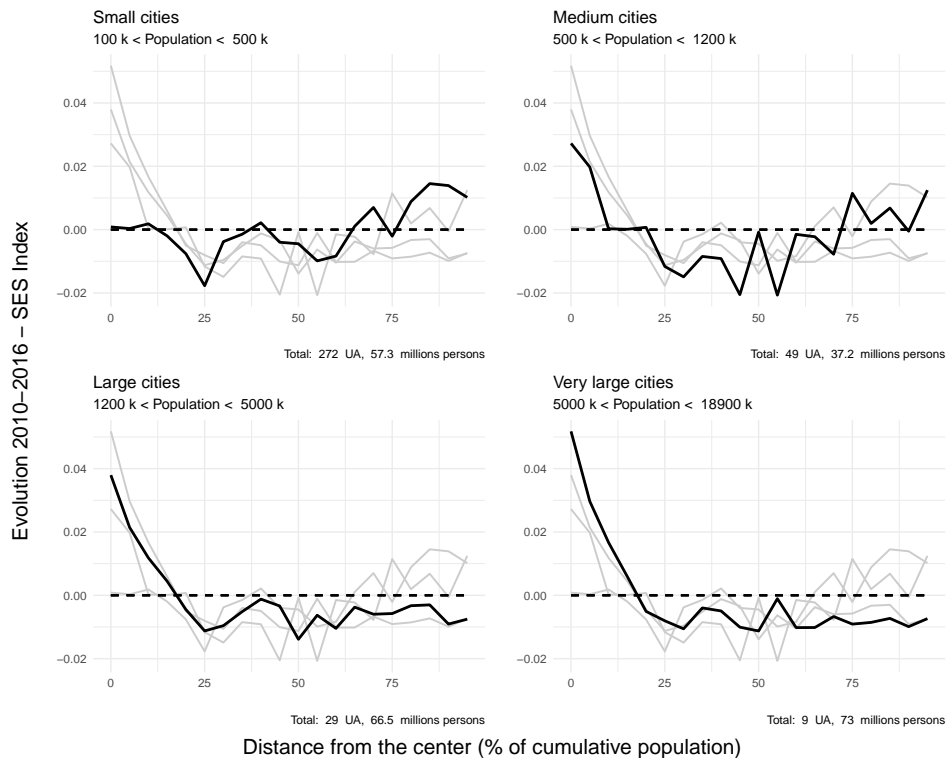


Figure 3.4: Evolution of the average Socioeconomic Status (SES) Index of Census Tracts between 2010 and 2016 as a function of distance to the center, for UA with different total populations. Source: American Community Survey 2010 and 2016.

Figure 3.3 shows that the current structures of US cities are consistent with the prediction of our model, but only very large cities, with a population above 5M, exhibit the structure with a U-shape relationship between income and distance. However, the analysis of figure 3.4 suggests that this structure may be generalizing to large cities, with population between 1M and 5M, if the trend observed in the recent years continues.

### 3.4 Conclusion

We introduce a simple, yet realistic, modification of household preferences for land consumption in the standard monocentric model. This introduction leads to two possible city

### 3.4. Conclusion

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configurations. Under this specification, the respective location of high- and low-income households varies with the overall levels of rents in the city. Therefore, our model links metropolitan-scale demand and supply of land/housing to a city’s internal structure.

Using local micro-data on US cities we show that the share of budget devoted to housing decreases with income, in line with the existing literature on housing demand. This confirms that our main assumption, the Stone-Geary specification for the utility function, is a realistic assumption. We document the fact that, as predicted by our model, households living in large cities tend to have relatively higher housing expenditures, all else equal.

The theoretical model predicts that small and medium cities have a monotonic and increasing relationship between income and distance from the center, while large cities have rich centers, poor inner suburbs, and rich outer suburbs. Using local data, we show that these predictions are consistent with the structure observed for US cities. The predictions are also consistent with the fact that inner-city gentrification is primarily observed in large metropolitan areas.

Considering housing as a necessity good may be particularly relevant to study current trends in US cities. We discussed in section 4.4 how our model to relate to the increase in transport “speed” of the second half of the 20<sup>th</sup> century. In recent years, populations kept increasing in large cities, local income inequalities rose, particularly in large cities (Baum-Snow and Pavan, 2013; Behrens and Robert-Nicoud, 2015; Baum-Snow et al., 2018), while transport speed arguably did not increase significantly.<sup>13</sup> Our simple model associates these trends with the trend of inner-city gentrification ongoing in large US cities. The model also suggests some insights on the distributional effects of urban equilibrium, as low-income residents tend to have higher housing budget shares as metropolitan income inequalities increase.

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<sup>13</sup>After an “adoption” phase of private cars, transport speed in cities may have decreased as a result of congestion.

# Appendices

## 3.A Existence and uniqueness of the equilibrium

### 3.A.1 Equilibrium with one income group

We first show that equilibrium with one income group exists if and only if the total population in the closed-city case<sup>14</sup> is below a maximal level  $N_{max}$ , and is unique.

Let us consider a city with homogeneous households (one group).  $\Psi(u, x)$  is the household's bid rent in  $x$ , and  $Q(u, x)$  is the bid-max lot-size. From equations 5.6 and 4.2, for any  $x$ :

$$\lim_{u \rightarrow 0} Q(u, x) = q_0$$

i.e. as utility decreases, land consumption decreases until it reaches  $q_0$ , the minimum possible land consumption. Similarly,  $\Psi(u, x)$  is bounded:

$$\lim_{u \rightarrow 0} \Psi(u, x) = \frac{Y-T}{q_0} \quad \text{and} \quad \forall u, x \quad \Psi(u, x) \leq \frac{Y-T}{q_0} \quad (3.9)$$

with the last inequality being strict if  $u > 0$ .

Equilibrium is defined by the fact that households' utility level is constant, reflecting their indifference across locations. At the equilibrium  $u(x) = \bar{u}$ ,  $R(x) = \Psi(\bar{u}, x)$ , and land consumption is  $q(x) = Q(\bar{u}, x)$ .

We assume that the border of the city  $x_{max}$  is located where rents fall to 0:

$$R(x_{max}) = \Psi(\bar{u}, x_{max}) = 0$$

Solving this equation leads to:  $T(x_{max}) = Y$ . We denote  $\Omega = [0, x_{max}]$  as the spatial extent of the city.

At each location  $x$ , land supply is  $\mu(x)$  and is exogenous. Population density at location  $x$  is  $\mu(x)/Q(u, x)$ . Total population in the city is obtained by summing up the population for every  $x$ :

$$N = \int_{\Omega} \frac{\mu(x)}{Q(\bar{u}, x)} .dx$$

We define the population  $N_{max}$  as:

$$N_{max} = \int_{\Omega} \frac{\mu(x)}{q_0} .dx$$

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<sup>14</sup>The equilibrium always exists in the open city case.



### 3.A. Existence and uniqueness of the equilibrium

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Given the transitivity of the integral, we have:

$$\lim_{u \rightarrow 0} \int_{\Omega} \frac{\mu(x)}{Q(\bar{u}, x)} \cdot dx = N_{max}$$

$N_{max}$  thus represents the upper population limit, above which the equilibrium does not exist. It corresponds to the limit case where households have a utility equal to 0 and live on lots of size  $q_0$ .

**Proposition 4.** *Let us consider a city in which income level  $Y$ , transport costs  $T(x)$ , and land supply  $\mu(x)$  are given. There is a bijection between utility level  $u$  and population  $N$ . More precisely, population  $N$  is strictly decreasing with utility level  $u$ .*

*Proof.* Combining equations 5.6 and 4.2 gives us a relationship between the utility level and lot sizes:

$$u(x) = (1 - \alpha)^{1-\alpha} (Y - T(x))^{1-\alpha} \left( 1 - \frac{\alpha q_0}{q(x) - (1 - \alpha)q_0} \right)^{1-\alpha} (q(x) - q_0)^\alpha \quad (3.10)$$

For  $q \in ]q_0; +\infty[$ ,  $u$  is strictly increasing when  $q$  is strictly increasing. This implies that the function  $u \rightarrow Q(u, x)$  is a bijection. If  $\mu(x)$  is exogenously given, we can infer that  $u \rightarrow N(u)$  is a strictly decreasing function, thus a bijection from  $]0; +\infty[$  to  $]0; N_{max}[$ .

Proposition 5 derives from 4. □

**Proposition 5.** *Equilibrium with one income group exists and is unique in the closed-city case, if and only if  $N < N_{max}$ .*

#### 3.A.2 Two income groups: two possible patterns

We now consider the model described in the main part of the paper: a city inhabited by people divided into two income groups:  $N_p$  households earning income  $Y_p$  and  $N_r$  earning  $Y_r$ , with  $Y_p < Y_r$ . For households of group  $i$ , we denote the bid rent  $\Psi_i(u_i, x)$  and the bid-max lot-size  $Q_i(u_i, x)$  ( $i = p, r$ ).

At each location, the two groups are in competition, and each location  $x$  will be occupied by the group with the higher bid rent. Rent at location  $x$  is:

$$R(x) = \max_{i=p \text{ or } r} \{\Psi_i(u, x)\}$$

The transport cost  $T(x)$  includes a monetary cost ( $\tau_1 x$ ) and an opportunity cost of time proportional to income ( $\tau_2 Y x$ ):  $T_i(x) = (\tau_1 + \tau_2 Y_i)x$

For  $i = p, r$ , we denote  $x_{max,i}$  as the solution to the equation  $T_i(x) = Y_i$ . We have:

$$x_{max,i} = \frac{Y_i}{\tau_1 + \tau_2 Y_i}$$

$x_{max,i}$  is thus larger for richer households. This implies that the outer periphery of the city is occupied by the high-income households group. We define  $\Omega = [0, x_{max,r}]$  as the spatial extent of the city.

From proposition 1, we derive a rent level  $R_{lim}$  above which the slope of the bid-rent gets steeper as income increases. We derive the following proposition from this result:

### 3.A. Existence and uniqueness of the equilibrium

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**Proposition 6** (Two configurations). *There can only be two city configurations: one with low-income households in the center and high-income households in the periphery, and another with high-income households in the center and outer periphery, and low-income households in the inner periphery.*

*Proof.* Let  $\bar{x} \in \Omega$  be an intersection point between the bid rents for high- and low-income households. Both bid rents are decreasing in  $x$ , therefore so is  $R(x) = \max(\Psi_p(x), \Psi_r(x))$ . We can thus distinguish two cases:

- If  $R(x=0) < R_{lim}$ , we know that for all  $x$ ,  $R(x) < R_{lim}$ , thus the bid rent for low-income households is steeper everywhere than bid rent for high-income households, and there can be only one intersection.
- If  $R(x=0) > R_{lim}$ , we can define the location  $x_{lim}$  so that  $R(x_{lim}) = R_{lim}$ . As the bid rents can be ordered by the relative steepness on the intervals  $[0, x_{lim}]$  and  $[x_{lim}, x_{max,r}]$ , there can only be one intersection on each of these intervals. Thus, there are at most two intersection points on  $\Omega$ . We also know that there must be at least one intersection between the bid rents. As high-income households occupy the outer suburbs, we infer that there is at least one intersection with low-income households on the outer location, thus on  $[x_{lim}, x_{max}]$ .<sup>15</sup>

□

#### 3.A.3 Market equilibrium with two income groups

Here, we derive the proof of proposition 3 that states the uniqueness of the equilibrium in a closed city with two income groups, *if this equilibrium exists*.

As indicated in 3.A.1, the minimum consumption of land implies that there are upper limits to the population in the city. With two income groups, the maximum population of each income group depends on the income and population of the other group. We do not derive sufficient criteria for the existence of an equilibrium. Proposition 3 only states that, if an equilibrium does exist given the model parameters, in the closed-city case, then it is unique.<sup>16</sup>

In the closed-city case, we define the equilibrium as a pair  $(u_p, u_r)$  of utility levels so that populations equal the given populations  $(N_p, N_r)$ . Proposition 3 states that the equilibrium is unique if it exists. Given income levels  $(Y_p, Y_r)$ , transport costs  $T(x)$ , and land supply  $\mu(x)$ , for any pair  $(N_p, N_r)$  only corresponds at most to one pair of utility levels  $(u_p, u_r)$  and one city configuration (*poor-rich* or *rich-poor-rich*).

The proof of proposition 3 is derived by contradiction. We first derive a few lemmas.

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<sup>15</sup>On the contrary, there can be one or zero intersections between the bid rents on  $[0, x_{lim}]$ . Thus, if  $R(x=0) > R_{lim}$ , we can be in configuration *a* or *b*.

<sup>16</sup>Note here that the existence and uniqueness of the equilibrium in the open-city case is straightforward, and is therefore not discussed here.

### 3.A. Existence and uniqueness of the equilibrium

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#### A few lemmas

To prove proposition 3, let us first demonstrate a few lemmas.

**Lemma 7.** *Let us consider a city where transport costs  $T(x)$  and land supply  $\mu(x)$  are given. Let us suppose that there is one income group. At any location  $x$ , the bid rent is strictly decreasing with the utility  $u$ , and strictly increasing with the population  $N$ . Especially, there is a bijection between utility level  $u$  and rent at the center  $R_0 = \Psi(x = 0)$ .*

*Proof.* Combining equations 5.6 and 4.2 gives a relationship between the utility level  $u$  and the bid-rent  $\Psi$ :

$$u = (1 - \alpha)^{1-\alpha} \alpha^\alpha (Y - T(x) - q_0 \cdot \Psi)^{1-\alpha} \left( \frac{Y - T(x)}{\Psi} + (1 - \alpha) \cdot q_0 \right)^\alpha$$

$u$  is strictly increasing when  $\Psi$  is strictly decreasing. Using prop. 4, we get that population  $N$  is also strictly increasing when  $\Psi$  is strictly decreasing, and reciprocally.  $\square$

**Lemma 8.** *Let us consider a city with 2 income groups, in which transport costs  $T_p(x)$  and  $T_r(x)$ , land supply  $\mu(x) > 0$  and income  $Y_p$  and  $Y_r$  are given. If the **utility** of one income group is given ( $u_p$  for instance), then the population of the other group ( $N_r$ ) is strictly decreasing with its utility ( $u_r$ ). The population of the other group  $N_p$  strictly decreases at the same time.*

*Proof.* Due to lemma 7,  $\Psi_r(x)$  increases as  $u_r$  decreases. If  $u_p$  is fixed, then decreasing  $u_r$  has two effects: first, it strictly decreases  $Q_r(u_r, x)$  and therefore strictly increases the density of high-income households in locations where  $\Psi_r(x) > \Psi_p(x)$ .

Second, it strictly increases the set of locations in which  $\Psi_r(x) > \Psi_p(x)$  (i.e. locations occupied by high-income households), which also strictly increases  $N_r$ , and strictly decreases  $N_p$ .  $\square$

**Lemma 9.** *Let us consider a city with 2 income groups, in which transport costs  $T_p(x)$  and  $T_r(x)$ , land supply  $\mu(x) > 0$  and income  $Y_p$  and  $Y_r$  are given. If the **population** of one income group is given ( $N_p$  for instance), then the population of the other group ( $N_r$ ) is strictly decreasing with its utility ( $u_r$ ).*

*Proof.* Proof by contradiction. Let us consider two situations :  $(N_p, N_r)$ , to which correspond the utility pair  $(u_p, u_r)$  and  $(N'_p, N'_r)$  with utility pair  $(u'_p, u'_r)$ . Let us suppose that  $N'_p = N_p$ , that  $u'_r < u_r$  and that  $N'_r < N_r$ .

According to lemma 8, if  $u'_p = u_p$ , then  $N'_p < N_p$ , and similarly, if  $u'_p < u_p$ , we see that  $N'_p < N_p$ , using the same proof as for this lemma. Therefore,  $u'_p > u_p$ .  $\square$

**Lemma 10.** *For  $f$  a differentiable function of two variables  $x$  and  $y$  on a set  $\Theta$ , then for all  $(x, y) \in \Theta$ :*

$$\frac{\partial}{\partial x} \left( \frac{1}{f(x, y)} \frac{\partial f}{\partial y}(x, y) \right) = \frac{\partial}{\partial y} \left( \frac{1}{f(x, y)} \frac{\partial f}{\partial x}(x, y) \right)$$

### 3.A. Existence and uniqueness of the equilibrium

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*Proof.* It can easily be verified by simple differentiation.  $\square$

**Lemma 11.** For any  $x$  in  $[0, x_f]$ :

$$\frac{d}{dx} \left( \frac{1}{\hat{Q}} \frac{d\hat{Q}}{dY} \right) > 0$$

*Proof.* First, note that, if  $f$  a differentiable function of two variables  $x$  and  $y$  on a set  $\Theta$ , then for all  $(x, y) \in \Theta$ :

$$\frac{\partial}{\partial x} \left( \frac{1}{f(x, y)} \frac{\partial f}{\partial y}(x, y) \right) = \frac{\partial}{\partial y} \left( \frac{1}{f(x, y)} \frac{\partial f}{\partial x}(x, y) \right)$$

This means that:

$$\frac{d}{dx} \left( \frac{1}{\hat{Q}} \frac{d\hat{Q}}{dY} \right) = \frac{d}{dY} \left( \frac{1}{\hat{Q}} \frac{d\hat{Q}}{dx} \right)$$

Deriving equation 4.2, we eventually get:

$$\frac{1}{\hat{Q}} \frac{d\hat{Q}}{dx} = -\frac{\alpha}{R} \frac{dR}{dx} \left( \frac{Y - T}{\hat{Q}R} \right) \quad (3.11)$$

Differentiating with respect to  $Y$  yields:

$$\frac{d}{dY} \left( \frac{1}{\hat{Q}} \frac{d\hat{Q}}{dx} \right) = -\frac{(1 - \alpha)\alpha q_0}{(\hat{Q}R)^2} \frac{dR}{dx} (1 - \tau_2 x) \quad (3.12)$$

By definition of  $x_{max}$ , we know that for  $x \in [0; x_{max}]$ ,  $1 - \tau_2 x > 0$ . As  $dR/dx < 0$ . This shows lemma 11.  $\square$

Finally, let us demonstrate the following lemma :

**Lemma 12.** Let  $f$  and  $g$  be two integrable functions on a subset  $\Theta$  of  $\mathbb{R}$ , and  $\Theta_1$  and  $\Theta_2$  two subsets of  $\Theta$ . Then:

$$\forall (x, y) \in \Theta_1 \times \Theta_2, f(x) > f(y) \Rightarrow \frac{\int_{\Theta_1} f(x)g(x)dx}{\int_{\Theta_1} g(x)dx} > \frac{\int_{\Theta_2} f(y)g(y)dy}{\int_{\Theta_2} g(y)dy}$$

*Proof.* Let us write:

$$\lambda = \frac{\min_{x \in \Theta_1}(f(x)) + \max_{x \in \Theta_2}(f(x))}{2}$$

$\forall x \in \Theta_1, f(x) > \lambda$ , and  $\forall x \in \Theta_2, f(x) < \lambda$ . By positivity of the integral, we then have:

$$\int_{\Theta_1} f(x)g(x)dx > \lambda \int_{\Theta_1} g(x)dx$$

$$\int_{\Theta_2} f(x)g(x)dx < \lambda \int_{\Theta_2} g(x)dx$$

These two inequalities show lemma 12.  $\square$

### 3.A. Existence and uniqueness of the equilibrium

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#### Demonstration

*Proof of proposition 3.* We prove proposition 3 by contradiction. Population is set at  $N_p$  for low-income households and  $N_r$  for high-income households, and we consider two pairs  $u_1 = (u_{1,p}, u_{1,r})$  and  $u_2 = (u_{2,p}, u_{2,r})$  of utility. We show that if  $u_1$  and  $u_2$  give population  $N = (N_p, N_r)$ , then  $u_1 = u_2$ .

There are several possible cases for  $u_1 = (u_{1,p}, u_{1,r})$  and  $u_2 = (u_{2,p}, u_{2,r})$ . An immediate case is if  $u_{1,r} > u_{2,r}$  and  $u_{1,p} < u_{2,p}$ . In this case, there is a direct contradiction due to lemma 8: the population of high-income households necessarily increase (high-income households occupy a larger zone in the city and have smaller dwellings, thus their population necessarily increase). The same reasoning is possible if  $u_{1,r} < u_{2,r}$  and  $u_{1,p} > u_{2,p}$ .

We now examine if  $u_{1,r} < u_{2,r}$  and  $u_{1,p} < u_{2,p}$ . We must here separate the cases when utilities  $u_1$  and  $u_2$  results in the same city configuration and the case when utilities  $u_1$  and  $u_2$  result in the *poor-rich* or *rich-poor-rich* configuration from figure 3.1 of section 4.4.

*Case 1.* Case (*poor-rich*) and (*poor-rich*)

We assume that  $u_1$  and  $u_2$  result in the *poor-rich* configuration. Let us also assume that  $u_1 \geq u_2$  for both high- and low-income households. Due to Eq. 3.10, for both high- and low-income households,  $Q(x, u_1) \geq Q(x, u_2)$ , with equality if and only if utilities are equal.

Let us write  $\Omega_{r,i}$  (resp.  $\Omega_{p,i}$ ) the subset of  $\Omega = [0; x_{max,r}]$  that is occupied by high-(resp. low-)income households under utility  $u_i$  ( $i = 1, 2$ ), and the associated land supply:  $\Theta_{r,1} = \int_{\Omega_{r,1}} \mu(x) dx$  (similarly  $\Theta_{p,i}$  for the low-income households).

There can only be three cases:

1.  $\Theta_{r,1} > \Theta_{r,2}$ ,  $\Theta_{p,1} < \Theta_{p,2}$ , meaning that low-income households occupy more space under utility  $u_2$  than under utility  $u_1$ . However, as  $Q_p(x, u_{1,p}) \geq Q_p(x, u_{2,p})$ , locations occupied by low-income households are more densely populated under utility  $u_2$ . As low-income households occupy more space (strictly), more densely, their population is strictly superior under utility  $u_2$ .
2. The converse case where  $\Theta_{r,2} > \Theta_{r,1}$  is also impossible as population of high-income households is necessarily higher under utility  $u_2$ .
3.  $\Theta_{r,1} = \Theta_{r,2}$  and  $\Theta_{p,1} > \Theta_{p,2}$ . In this case, since we have:  $\mu(x)/Q(x, u_1) \leq \mu(x)/Q(x, u_2)$  for all  $x$  and for both high- and low-income households. The positivity of the integral entails that population can be equal if and only if  $u_1 = u_2$

### 3.A. Existence and uniqueness of the equilibrium

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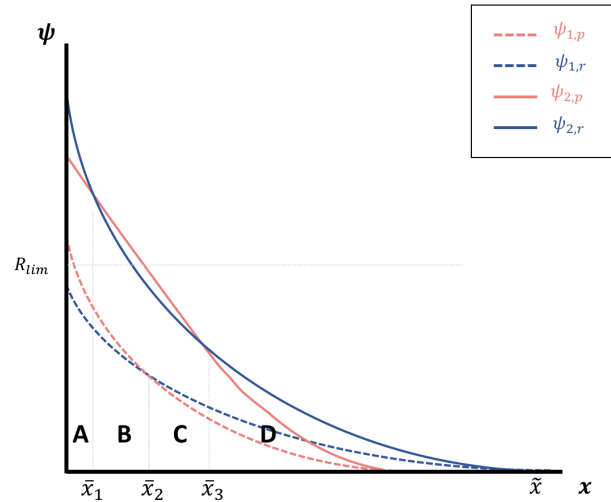


Figure 3.A.1: Bid-rents for high- and low-income households in the configurations 1 (*poor-rich*) and 2 (*rich-poor-rich*).

By contradiction, we show that the only possibility for the populations to be equal is that the rents at the center be equal, thus that  $u_1 = u_2$  from lemma 7.

*Case 2.* Case (*rich-poor-rich*) and (*rich-poor-rich*)

Demonstration in this case is exactly similar to the previous case.

*Case 3.* Case (*poor-rich*) and (*rich-poor-rich*)

Let us consider that  $u_1$  results in *poor-rich* configuration, and  $u_2$  results in *rich-poor-rich* configuration.

Figure 3.A.1 illustrates the bid-rents  $\Psi_1 = (\Psi_{1,poor}, \Psi_{1,rich})$  and  $\Psi_2 = (\Psi_{2,poor}, \Psi_{2,rich})$  for utilities  $u_1$  and  $u_2$ . Let us compare the populations between the two configurations for the four zones  $A = [0, \bar{x}_1]$ ,  $B = [\bar{x}_1, \bar{x}_2]$ ,  $C = [\bar{x}_2, \bar{x}_3]$  and  $D = [\bar{x}_3, \hat{x}]$ .

Both utility vectors  $u_1$  and  $u_2$  result in the same populations  $(N_p, N_r)$ . For low-income households, this writes:

$$N_1^A + N_1^B = N_2^B + N_2^C$$

where  $N_j^k$  is the population in zone  $k = A, B, C, D$  under utility  $u_j$ . Since bid rents are higher for configuration 2 than for configuration 1, and given that the land supply is fixed, we have  $N_1^B < N_2^B$ . Therefore, equating the

### 3.A. Existence and uniqueness of the equilibrium

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population of low-income household implies:

$$N_1^A > N_2^C$$

For high-income households, it must hold similarly that  $N_1^C + N_1^D = N_2^A + N_2^D$ . Since  $N_1^D < N_2^D$ , we must have:  $N_1^C > N_2^A$

The total land supply on the interval  $A$  is:  $\Theta_A = \int_A \mu(x).dx$ . We define similarly  $\Theta_B$ ,  $\Theta_C$  and  $\Theta_D$ .

We define the average dwelling size on the interval  $A$  as:

$$\langle q_{j,i}^A \rangle = \frac{\int_A \mu(x)(x).dx}{\int_A \frac{\mu(x)(x)}{\hat{Q}_i(x, u_j)}.dx}$$

where  $\hat{Q}_i(x, u_j)$  is the bid lot-size of households  $i = r, p$  when the rent equals the maximum of the bid-rents  $R(x)$  in configuration  $j = 1, 2$ , that is:

$$\hat{Q}_i(x, u_j) = \alpha \frac{Y_i - T_i(x)}{R(x; u_j)} + (1 - \alpha).q_0$$

The difference between  $N_1^C$  and  $N_2^A$  for rich households must be positive, that is:

$$\begin{aligned} 0 < N_1^C - N_2^A &= \int_C \frac{\mu(x)}{Q_r(x, u_1)}.dx - \int_A \frac{\mu(x)}{Q_r(x, u_2)}.dx \\ &= \frac{\Theta_C}{\langle q_{1,r}^C \rangle} - \frac{\Theta_A}{\langle q_{2,r}^A \rangle} \end{aligned}$$

Leading to:

$$\begin{aligned} 0 > \frac{\langle q_{1,r}^C \rangle}{\Theta_C} - \frac{\langle q_{2,r}^A \rangle}{\Theta_A} &= \left[ \frac{\langle q_{1,r}^C \rangle}{\Theta_C} - \frac{\langle q_{2,r}^C \rangle}{\Theta_C} \right] + \left[ \frac{\langle q_{2,r}^C \rangle}{\Theta_C} - \frac{\langle q_{2,r}^A \rangle}{\Theta_C} \right] + \left[ \frac{\langle q_{2,r}^A \rangle}{\Theta_C} - \frac{\langle q_{2,r}^A \rangle}{\Theta_A} \right] \\ &= \frac{\langle q_{1,r}^C \rangle - \langle q_{2,r}^C \rangle}{\Theta_C} + \frac{\langle q_{2,r}^C \rangle - \langle q_{2,r}^A \rangle}{\Theta_C} + \langle q_{2,r}^A \rangle \left[ \frac{1}{\Theta_C} - \frac{1}{\Theta_A} \right] \end{aligned} \quad (3.13)$$

Since the bid max lot-size is decreasing in  $x$  and increasing in  $u$ , we have:  $\langle q_{1,r}^C \rangle > \langle q_{1,r}^A \rangle$  and  $\langle q_{1,r}^C \rangle > \langle q_{2,r}^C \rangle$ . Since  $N_1^C - N_2^A < 0$ , it must hold that  $\Theta_A < \Theta_C$ .

Similarly, for low-income households:

$$\begin{aligned} 0 > \frac{\langle q_{1,p}^A \rangle}{\Theta_A} - \frac{\langle q_{2,p}^C \rangle}{\Theta_A} &= \left[ \frac{\langle q_{1,p}^A \rangle}{\Theta_A} - \frac{\langle q_{2,p}^A \rangle}{\Theta_A} \right] + \left[ \frac{\langle q_{2,p}^A \rangle}{\Theta_A} - \frac{\langle q_{2,p}^A \rangle}{\Theta_C} \right] + \left[ \frac{\langle q_{2,p}^A \rangle}{\Theta_C} - \frac{\langle q_{2,p}^C \rangle}{\Theta_C} \right] \\ &= \frac{\langle q_{1,p}^A \rangle - \langle q_{2,p}^A \rangle}{\Theta_A} + \langle q_{2,p}^A \rangle \left[ \frac{1}{\Theta_A} - \frac{1}{\Theta_C} \right] + \frac{\langle q_{2,p}^A \rangle - \langle q_{2,p}^C \rangle}{\Theta_C} \end{aligned} \quad (3.14)$$

### 3.A. Existence and uniqueness of the equilibrium

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Dividing equations 3.13 by  $\langle q_{2,r}^A \rangle$ , dividing equation 3.14 by  $\langle q_{2,p}^A \rangle$  and summing, we get:

$$\frac{\langle q_{1,r}^C \rangle - \langle q_{2,r}^C \rangle}{\langle q_{2,r}^A \rangle \Theta_C} + \frac{\langle q_{2,r}^C \rangle - \langle q_{2,r}^A \rangle}{\langle q_{2,r}^A \rangle \Theta_C} + \frac{\langle q_{1,p}^A \rangle - \langle q_{2,p}^A \rangle}{\langle q_{2,p}^A \rangle \Theta_A} + \frac{\langle q_{2,p}^A \rangle - \langle q_{2,p}^C \rangle}{\langle q_{2,p}^A \rangle \Theta_C} < 0$$

Since  $u_{1,r} < u_{2,r}$  and  $u_{1,p} < u_{2,p}$ , we have  $\langle q_{1,r}^C \rangle > \langle q_{2,r}^C \rangle$  and  $\langle q_{1,p}^A \rangle > \langle q_{2,p}^A \rangle$ . This implies:

$$\begin{aligned} \frac{\langle q_{2,r}^C \rangle - \langle q_{2,r}^A \rangle}{\langle q_{2,r}^A \rangle \Theta_C} + \frac{\langle q_{2,p}^A \rangle - \langle q_{2,p}^C \rangle}{\langle q_{2,p}^A \rangle \Theta_C} &< 0 \\ \iff \frac{\langle q_{2,r}^C \rangle}{\langle q_{2,r}^A \rangle} &< \frac{\langle q_{2,p}^C \rangle}{\langle q_{2,p}^A \rangle} \\ \iff \frac{\int_A \frac{\mu(x)}{\hat{Q}_r(x, u_1)} dx}{\int_C \frac{\mu(x)}{\hat{Q}_r(x, u_1)} dx} &< \frac{\int_A \frac{\mu(x)}{\hat{Q}_p(x, u_1)} dx}{\int_C \frac{\mu(x)}{\hat{Q}_p(x, u_1)} dx} \end{aligned} \quad (3.15)$$

We use the lemmas from the last section to show that equation 3.15 cannot hold. First, let us derive with respect to income:

$$\begin{aligned} \frac{d}{dY} \left( \frac{\int_A \frac{\mu(x)}{\hat{Q}(x)} dx}{\int_C \frac{\mu(x)}{\hat{Q}(x)} dx} \right) &= \frac{\int_A -\frac{d\hat{Q}}{dY} \frac{\mu(x)}{\hat{Q}(x)^2} dx \int_C \frac{\mu(x)}{\hat{Q}(x)} dx - \int_A \frac{\mu(x)}{\hat{Q}(x)} dx \int_C -\frac{d\hat{Q}}{dY} \frac{\mu(x)}{\hat{Q}(x)^2} dx}{\left( \int_C \frac{\mu(x)}{\hat{Q}(x)} dx \right)^2} \\ &= \frac{\int_C \frac{d\hat{Q}}{dY} \frac{\mu(x)}{\hat{Q}(x)^2} dx}{\int_C \frac{\mu(x)}{\hat{Q}(x)} dx} - \frac{\int_A \frac{d\hat{Q}}{dY} \frac{\mu(x)}{\hat{Q}(x)^2} dx}{\int_A \frac{\mu(x)}{\hat{Q}(x)} dx} \frac{\int_A \frac{\mu(x)}{\hat{Q}(x)} dx \int_C \frac{\mu(x)}{\hat{Q}(x)} dx}{\left( \int_C \frac{\mu(x)}{\hat{Q}(x)} dx \right)^2} \end{aligned} \quad (3.16)$$

Using lemma 11, we obtain:

$$\forall (x_1, x_2) \in A \times C, \frac{1}{\hat{Q}(x_1)} \frac{d\hat{Q}}{dY}(x_1) < \frac{1}{\hat{Q}(x_2)} \frac{d\hat{Q}}{dY}(x_2)$$

Lemma 12 implies that:

$$\frac{\int_C \frac{d\hat{Q}}{dY} \frac{\mu(x)}{\hat{Q}(x)^2} dx}{\int_C \frac{\mu(x)}{\hat{Q}(x)} dx} > \frac{\int_A \frac{d\hat{Q}}{dY} \frac{\mu(x)}{\hat{Q}(x)^2} dx}{\int_A \frac{\mu(x)}{\hat{Q}(x)} dx} \quad (3.17)$$

Combining 3.17 and 3.16, we get:

$$\frac{d}{dY} \left( \frac{\int_A \frac{\mu(x)}{\hat{Q}(x)} dx}{\int_C \frac{\mu(x)}{\hat{Q}(x)} dx} \right) > 0$$



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In particular, this implies that:

$$\frac{\int_A \frac{\mu(x)}{\tilde{Q}_r(x, u_1)} dx}{\int_C \frac{\mu(x)}{\tilde{Q}_r(x, u_1)} dx} > \frac{\int_A \frac{\mu(x)}{\tilde{Q}_p(x, u_1)} dx}{\int_C \frac{\mu(x)}{\tilde{Q}_p(x, u_1)} dx}$$

which is in direct contradiction with equation 3.15.

□

## 3.B Comparative statics in a city with two income groups

In this section, we study the predictions of the model regarding the effect of an increasing population, decreasing land supply, and increasing transport costs on the relative location of households depending on their income. We present here analytical results as well as the outcomes of numerical simulations. Details on the value of the parameters used in the simulations can be found in 3.C.

### 3.B.1 Effect of city population

In the closed-city case of the monocentric model, a higher population results in higher overall rents (Fujita, 1989, p.77 and p.124), as the demand for residential land is higher. Such results also hold in our model, and we show that it also tends to favor the presence of high-income households in the center. In particular, we show that:

**Proposition 13** (Necessary condition for the *rich-poor-rich* configuration). *Let us consider a city in which income levels  $(Y_p, Y_r)$ , transport costs  $T_i(x) = (\tau_1 + \tau_2 Y_i) \cdot x$ , and land supply  $\mu(x)$  are given. In the closed-city case, there exists a minimum population  $N^-$  under which only the poor-rich configuration is possible.*

and

**Proposition 14** (Sufficient condition for the *rich-poor-rich* configuration). *If  $\tau_1 \cdot \frac{\alpha}{1-\alpha} > \tau_2 \cdot Y_p$ , we can construct a pair of population  $(N_p^+ > 0, N_r^+ > 0)$ , for which an equilibrium exists, and such that for every each other pair  $(N'_p, N'_r)$ , if  $N'_p \geq N_p^+$  and  $N'_r \geq N_r^+$ , with one of the two inequalities being strict, then the city is always in the "rich-poor-rich" configuration if the equilibrium exists.*

In order to prove these propositions, we first present a few useful lemmas. Let us consider a city with two income groups, in which income levels  $(Y_p, Y_r)$ , transport costs  $T(x)$  and land supply  $\mu(x) > 0$  are given.

**Lemma 15** ("High-income households are better off if there are also low-income households in the city"). *If there are both high- and low-income households in the city ( $N_p > 0$  and  $N_r > 0$ ), with a total population  $N_p + N_r = N$ , then the utility of **high-income** households is **higher** than the utility they would have if all the  $N$  inhabitants of the city where rich.*

*Proof.* If  $N_p > 0$  and  $N_r > 0$ , there are places in the city in which low-income households are located, i.e. where  $\Psi_p > \Psi_r$ . In these places, population density is given by:

$$n_p(x) = \frac{\mu(x)}{Q_p(x, u_p)}$$

We have:

$$Q_p(x, u_p) = \alpha \frac{Y_p - \tau_1 \cdot x - \tau_2 \cdot Y_p \cdot x}{\Psi_p(x)} + (1 - \alpha) \cdot q_0$$

### 3.B. Comparative statics in a city with two income groups

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For all  $x \in \Omega$ ,  $Y_p - \tau_1 \cdot x - \tau_2 \cdot Y_p \cdot x > 0$ , therefore:

$$Q_p(x, u_p) < \alpha \frac{Y_r - \tau_1 \cdot x - \tau_2 \cdot Y_r \cdot x}{\Psi_p(x)} + (1-\alpha) \cdot q_0 < \alpha \frac{Y_r - \tau_1 \cdot x - \tau_2 \cdot Y_r \cdot x}{\Psi_r(x)} + (1-\alpha) \cdot q_0 = Q_r(x, u_r)$$

where we have successively replaced  $Y_p$  by  $Y_r > Y_p$  and  $\Psi^p(x)$  by  $\Psi_r(x) < \Psi_p(x)$ . We therefore have  $n_p(x) = \mu(x)/Q_p(x, u_p) > \mu(x)/Q_r(x, u_r)$  where  $\mu(x)/Q_r(x, u_r)$  is the population density that high-income households would have if they were living in  $x$ .

$u_r$  is the utility of the high-income households when there are low-income households in the city. If they had this utility but there were only high-income households, the population density would be  $\mu(x)/Q_r(x, u_r)$  for all  $x \in \Omega$ , so the total population of the city would be smaller. Conversely, if they were the only inhabitants of the city and we fix  $N_r = N$ , their utility would be smaller.  $\square$

**Lemma 16.** *To any population pair  $(N'_p, N'_r)$  with  $N'_p \geq N_p$  and  $N'_r \geq N_r$ , one of the two inequalities being strict, correspond a utility pair  $(u'_p < u_p, u'_r < u_r)$ .*

*Proof.* To the population pair  $(N'_p > N_p, N_r)$  correspond utilities  $(u_p^1 < u_p, u_r^1 < u_r)$  based on lemma 9. To the population pair  $(N'_p > N_p, N_r \geq N_r)$  thus correspond utilities  $(u_p^2 \leq u_p^1 < u_p, u_r^2 \leq u_r^1 < u_r)$ . A similar computation can be done for the pair  $(N'_p \geq N_p, N_r > N_r)$ .  $\square$

We can now prove prop. 13 and prop. 14.

*Proof of prop. 13 (Necessary condition for a gentrified city).* According to prop. 6, if everywhere in the city rents are lower than  $R_{lim} = \tau_1 \alpha / \tau_2 (1 - \alpha) q_0$ , then the city has the *poor-rich* configuration.

Using lemma 7, we denote  $N^-$  the population of high-income households below which the bid rent  $\Psi_r$  would be below  $R_{lim}$  everywhere in the city, if there were only high-income households in the city. Lemma 15 means that, if the city total population is given,  $\Psi_r$  is lower when there are both high- and low-income households than when there are only high-income households. So, if the total population of the city is lower than  $N^-$ ,  $\Psi_r$  is lower than  $R_{lim}$  everywhere.

This means that, when  $\Psi_r$  and  $\Psi_p$  intersect, they are lower than  $R_{lim}$ , and so the city is necessarily in the configuration *poor-rich*.  $\square$

*Proof of prop. 14 (Sufficient condition for a gentrified city).* High-income households live in the center of the city if the bid rent of low-income households in the center of the city ( $x = 0$ , i.e. where  $T = 0$ ) is lower than the bid rent of high-income households in this location. Due to eq. 3.9 the bid-rent  $\Psi_p$  of low-income households in the center of the city (where  $T = 0$ ) is bounded by  $\frac{Y_p}{q_0}$ , and the bid rent  $\Psi_r$  of high-income households by  $\frac{Y_r}{q_0} > \frac{Y_p}{q_0}$ .

According to lemma 7, there exists a minimum utility level  $u_r^+$  for high-income households such that  $\Psi_r(x = 0) > Y_p/q_0$ . Therefore, if  $u_r > u_r^+$ , high-income households live

### 3.B. Comparative statics in a city with two income groups

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in the center of the city, and the city is always in the *rich-poor-rich* configuration if the number of low-income households is greater than 0.

To sum up, we have showed that there exists a minimum utility level  $u_r^+$  for high-income households, such that for all utility levels  $u_p$  for low-income households and all utility levels  $u_r > u_r^+$  for high-income households, the city is always in the *rich-poor-rich* configuration if the number of low-income households is greater than 0.

We consider utilities  $(u_p, u_r > u_r^+)$  with corresponding populations  $(N_p, N_r)$ . According to lemma 7, to any population pair  $(N'_p, N'_r)$  with  $N'_p \geq N_p$  and  $N'_r \geq N_r$ , one of the two inequalities being strict, correspond a utility pair  $(u'_p > u_p, u'_r > u_r)$ . Since  $u'_r > u_r > u_r^+$ , the city is still in the *rich-poor-rich* configuration.

This proves the first part of the proposition. We now prove the second part, that is: if  $\tau_1 \cdot \alpha / (1 - \alpha) > \tau_2 \cdot Y_p$ , the equilibrium exists for at least one of these pairs.

To prove this, note that in the limit case  $(u_p = 0, u_r = u_r^+)$ , the bid rents in the center are equal by construction:

$$\Psi_p(x = 0, u_p = 0) = \Psi_r(x = 0, u_r = u_r^+) = \frac{Y_p}{q_0}$$

According to lemma 1, since  $\tau_1 \cdot \frac{\alpha}{1 - \alpha} > \tau_2 \cdot Y_p$ , the bid rent is steeper for high-income households, so the bid rent of high-income households is below the bid rent of low-income households in the vicinity of  $x = 0$ . In this configuration, low-income households live in the vicinity of  $x = 0$ , and therefore  $N_p > 0$  (as shown in 3.A.2, high-income households always live at the outskirts of the city, so we always have  $N_r > 0$ ).

Also the slope of bid-rents is equal to the marginal transport cost divided by the bid lot size, that is:

$$\frac{\partial \Psi_i(u_i, x)}{\partial x} = - \frac{(\tau_1 + \tau_2 Y_i)}{\alpha \frac{Y_i - (\tau_1 + \tau_2 Y_i) \cdot x}{\Psi_i(u_i, x)} + (1 - \alpha) \cdot q_0}$$

where  $i = r, p$ . The slope is therefore increasing (in absolute terms), with the value of the bid rent: for a given  $x$  and a given  $Y_i$ , the lower the bid rent, the less steep it is, or, equivalently, for a given  $x$  and a given  $Y_i$ , the higher the utility  $u_i$ , the less steep the bid rent. This means that any bid-rent  $\Psi_p(x, u_p > 0)$  will be less steep than the bid rent  $\Psi_p(x, u_p = 0)$ .

As a consequence, any bid rent  $\Psi_p(x, u_p > 0)$  will have the following properties:

- $\Psi_p(x = 0, u_p > 0) < \Psi_r(x = 0, u_r = u_r^+)$
- $\frac{\partial \Psi_p}{\partial x}(x = 0, u_p > 0) > \frac{\partial \Psi_r}{\partial x}(x = 0, u_r = u_r^+)$

It is straightforward to show that there exist  $\epsilon > 0$  such that in  $x = 0$  the bid rent  $\Psi_p(x, u_p = \epsilon)$  is lower than the bid rent  $\Psi_r(x, u_r = u_r^+)$  of high-income households, but becomes higher in a vicinity. This ensures that, with the utility pair  $(u_p = \epsilon, u_r = u_r^+)$ , we have at the same time  $N_p > 0, N_r > 0$  and the high-income households in the center of the city.  $\square$

### 3.B. Comparative statics in a city with two income groups

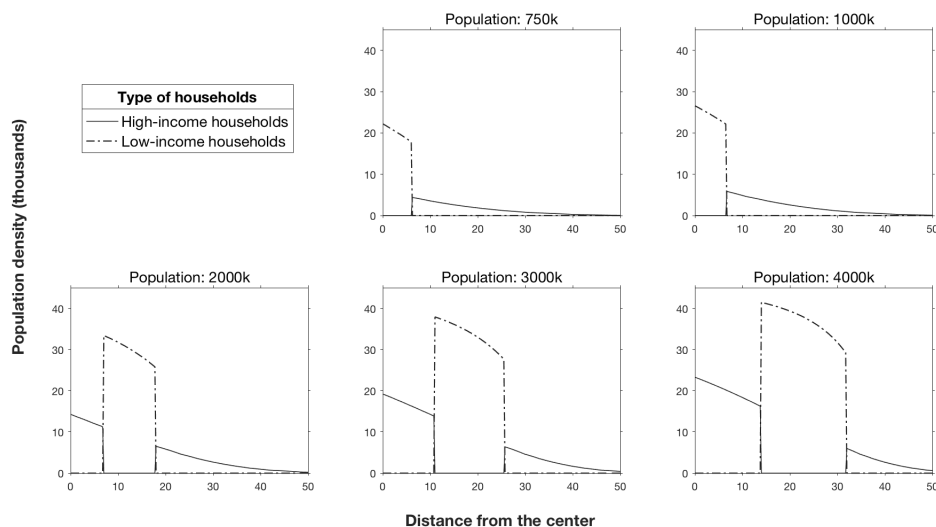


Figure 3.B.1: Simulated density of low-income (dotted line) and high-income (continuous line) households as a function of distance to the center in cities with identical characteristics except for different total population levels. Parameters used for the simulation are presented in 3.C.

As an illustration, figure 3.B.1 shows the results of a numerical simulation. For low populations, the city is in a *poor-rich* configuration, and a population increase does not change the structure. However, there is a tipping point between 1 and 2 million households, above which the city's structure becomes *rich-poor-rich*. Above this threshold, low-income households tend to live in locations that are further from the center as the population increases. Because they occupy smaller plots of land, low-income households live in more densely populated areas.

#### 3.B.2 Effect of land or housing availability

Land (or housing) availability plays an inverse role to total population: increasing its availability  $\mu(x)$  tends to decrease rents. We show that there is a minimum level of  $\mu(x)$  below which the city will be in the *rich-poor-rich* configuration. The two following propositions are similar to the propositions on the effect of city population.

**Proposition 17** (Necessary condition for the *rich-poor-rich* configuration). *Let us consider a city with income levels  $(Y_p, Y_r)$ , transport costs  $T_i(x) = (\tau_1 + \tau_2 Y_i) \cdot x$ , and a population pair  $(N_p, N_r)$ . In the closed-city case, there exists a land availability function  $\mu^+(x)$  above which only the poor-rich configuration is possible.*

**Proposition 18** (Sufficient condition for the *rich-poor-rich* configuration). *If  $\tau_1 \cdot \frac{\alpha}{1-\alpha} > \tau_2 \cdot Y_p$ , there exists a land availability function  $\mu^-(x)$  for which the equilibrium exists, such that, for any other function  $\mu'(x) < \mu^-(x)$ , if the equilibrium exists, the city is in the rich-poor-rich configuration.*

### 3.B. Comparative statics in a city with two income groups

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*Proof.* The proofs of these propositions can be derived directly from the propositions on the effect of population. If we multiply the land availability function by a constant  $\gamma$ , the population is multiplied by  $\gamma$ , but everything else remains the same. Therefore, in a given city, the effect on rents, utilities, and so on is the same if we multiply by  $\gamma$  the land availability function  $\mu(x)$  while keeping  $N_r$  and  $N_p$  constant, or if we keep  $\mu(x)$  constant but divide  $N_r$  and  $N_p$  by  $\gamma$ . From proposition 14, it is straightforward to show that from a land availability function  $\mu(x)$ , we can find constants  $\gamma^+$  and  $\gamma^-$  such that the functions  $\mu^+(x) = \gamma^+\mu(x)$  and  $\mu^-(x) = \gamma^-\mu(x)$  meet the conditions of prop. 17 and 18.  $\square$

#### 3.B.3 Effect of income distribution

We can model variations in income distribution in two ways: (i) a change in the income ratio  $Y_p/Y_r$ , and (ii) a change in the population ratio  $N_r/N_p$ . Let us first consider that the income of low-income households remains constant at  $Y_p$ , and that the income of high-income households reaches a new level  $Y_r' > Y_r$ .

**Proposition 19** (Income ratio change). *Let us consider that the population in a city is given by the pair  $(N_p, N_r)$  and incomes by  $(Y_p, Y_r)$ . If the equilibrium exists, then there is an income  $Y_r^+$  for high-income households such that  $Y_r^+ > Y_p$ , an equilibrium exists, and the city is in the rich-poor-rich configuration. Moreover, for  $Y_r' > Y_r^+$ , if an equilibrium exists, the city is in the rich-poor-rich configuration.*

The same mechanism occurs if we increase the share of high-income households while total population remains constant.

**Proposition 20** (Change in the share of high-income households). *Let us consider that the population in a city is given by the pair  $(N_p, N_r)$  and incomes by  $(Y_p, Y_r)$ . If the equilibrium exists, then there is a population of high-income households  $N_r^+$  such that an equilibrium exists and the city is in the rich-poor-rich configuration. Moreover, for  $N_r' > N_r^+$ , if the equilibrium exists, the city is in the rich-poor-rich configuration.*

The proof of these two propositions follow the same exact logic as the proof in 3.B.1. We first need to show that “low-income households are worse off if there are also high-income households in the city”, and that “low-income households are worse off if high-income are richer” (equivalent to lemma 15). This derives directly from the normality of land. Then we show that we can derive an equilibrium such that  $\Psi_r(x=0) > \frac{Y_p}{q_0}$ , by adjusting either the share of high-income households or the income of high-income households. This equilibrium is such that any increase in  $N_r$  or any increase in  $Y_r$  will result in the *rich-poor-rich* configuration. We do not derive the formal proof here.

Figure 3.B.2 shows the density of households as a function of distance for cities with different income ratios of high-income to low-income households. As the ratio increases, land becomes relatively more expensive for low-income households, and the city shifts to a *rich-poor-rich* configuration.

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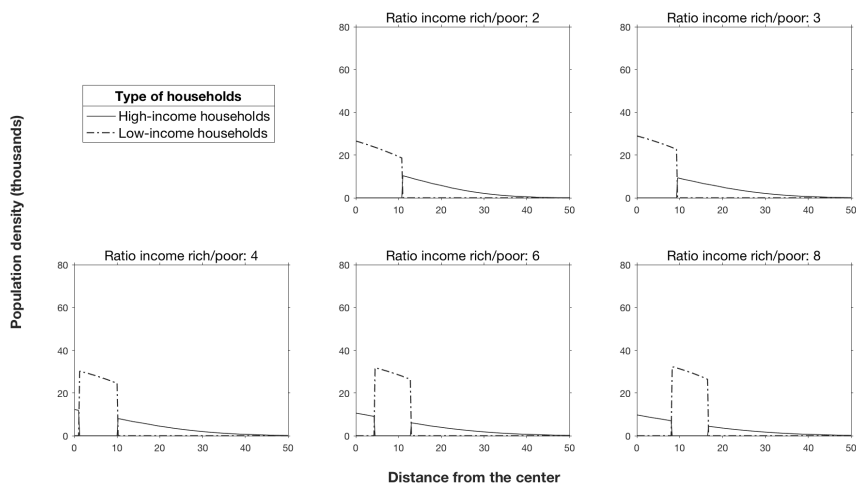


Figure 3.B.2: Simulated density of low-income (dotted line) and high-income (continuous line) households as a function of distance to the center in cities with identical characteristics except for different levels of income inequality. Income for high-income households vary while income of low-income households remains constant. Other parameters used for the simulation are presented in 3.C.

#### 3.B.4 Effect of transport costs and speed

We discuss here the impact of transport costs (parameter  $\tau_1$ ) and speed (inverse of parameter  $\tau_2$ ) on city structure. The effect of transport speed on city structure is straightforward: when transport speed increases (i.e.,  $\tau_2$  decreases), low-income households tend to live in the city center and high-income households in suburban locations.

**Proposition 21** (Change in transport speed). *There is a minimal value for  $\tau_2$  under which, if the equilibrium exists, the city is always in the poor-rich configuration.*

*Proof.* As speed increases, the coefficient  $\tau_2$  decreases. Thus, the city is more sprawled, and the rents decrease. Moreover, the rent  $R_{lim}$  increases, while the bid rent of high-income households is steeper above the rent  $R$  (see condition from equation 3.2.4). Thus, as  $\tau_2$  decreases (speed of transport increases), low-income households tend to live in the city center and high-income households tend to live in suburban locations.  $\square$

The effect of a change in transport monetary cost is more complex. As transport costs increase, bid rents become steeper, the city is more compact, and rents increase in the center (all other parameters being equal). Rent increases tend to push low-income households to suburban locations (as it decreases the income elasticity of demand for land). However, increasing transport monetary costs also attracts low-income households to the center because it decreases the income elasticity of transport costs. As this decreases both the income elasticity of transport costs and demand for land, the effect of an increase in transport monetary costs is ambiguous and depends on the characteristics

### 3.B. Comparative statics in a city with two income groups

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of the city (e.g. population, land supply, transport speed). Figure 3.B.3 shows the result of a simulation with the parameters specified in 3.C. The result of this simulation is that as the monetary cost of commuting increases, low-income residents tend to live closer to the center, suggesting that, in this case, the “transport cost” effect dominates the “land demand” effect.

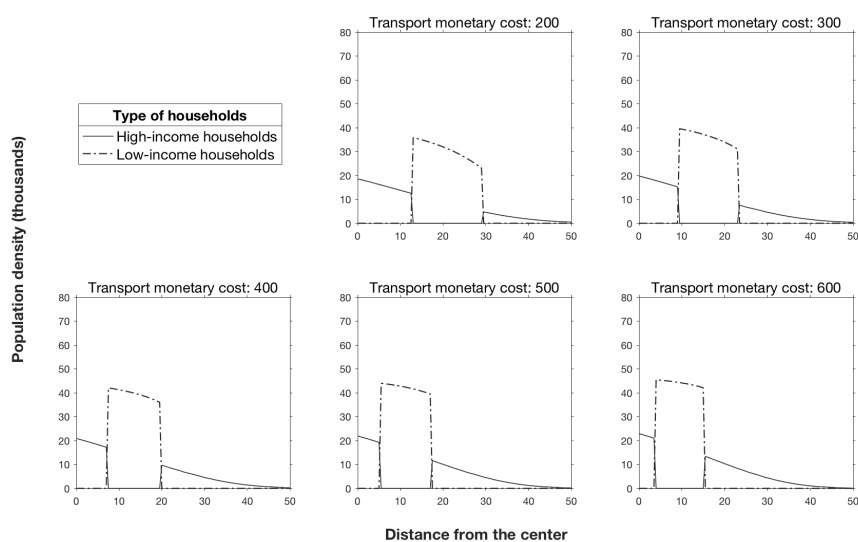


Figure 3.B.3: Simulated density of low-income (dotted line) and high-income (continuous line) households as a function of distance to the center, in cities with identical characteristics except for different monetary cost of transport per unit of distance. Other parameters used for the simulation are presented in 3.C.



### 3.C. Parameters for the numerical simulations

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### 3.C Parameters for the numerical simulations

Table 3.C.1 gives the value of the parameters used for the simulations presented in 3.B, except if specified otherwise. For simplicity, the exogenous land supply is taken as a constant function  $\mu(x) = \mu$  in the simulation<sup>17</sup>.

| Parameter                                 | Notation    | Value          |
|---|-------------|----------------|
| Utility function                          | $\alpha$    | 0.2            |
| Utility function - Minimum amount of land | $q_0$       | 10             |
| Income rich                               | $Y_r$       | 150,000        |
| Income poor                               | $Y_p$       | 30,000         |
| Transport - Monetary cost                 | $\tau_1$    | 250            |
| Transport - Cost of time                  | $\tau_2$    | 1/80           |
| Ratio of population between rich and poor | $N_r/N_p$   | 1/2            |
| Total population                          | $N_r + N_p$ | 1,000,000      |
| Land availability by unit of distance     | $\mu$       | $2 \cdot 10^6$ |

Table 3.C.1: Value for the parameters used in the numerical simulations presented in the appendix.

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<sup>17</sup>This corresponds to a linear city. We could also consider a two-dimensional city for which  $\mu(x)$  is proportional to  $x$ . Qualitative results would be equivalent.

## 3.D Supplementary results on the structure of U.S. Cities

We use the same index for socioeconomic status (SES) as Hwang and Lin (2016). The SES Index of a census tract is the percentile rank, within an Urbanized Area (UA), of the average between (i) its rank in share of college graduates among population aged between 25 and 64 years and (ii) its rank in median households income. This index ranks between 0 (low socioeconomics status) and 1 (high SES). We use data from the American Community Survey 2010 and 2016 at the census tract level.

For all the following graphs, we use Origin-Destination Employment Statistics of the 2014 Longitudinal Employer-Household Dynamics (LEDH) data to define each UA's center ("CBD"). For every tract, we consider the averaged employment density for the tracts and its adjacent ones. The CBD is the centroid of the tract with the highest corresponding average job density in the UA. The distance to this center is expressed as cumulative total population of the UA from 2016 American Community Survey.

Figures 3.D.1 and 3.D.2 show the share of college-educated and the median income as a function of the distance from the center. Both variables were used to compute the SES indexes in figure 3.3. The same patterns are seen for each of these variables.

Figures 3.D.3 and 3.D.4 present similar graphs than figure 3.3 for the share of college-educated and the median income, respectively.

### 3.D. Supplementary results on the structure of U.S. Cities

#### 3.D.1 Share of college-educated in 2016



Figure 3.D.1: Share of college graduates among population aged between 25 and 64 years as a function of distance to the center for US Urbanized Areas with different total populations. Source: American Community Survey 2016.

### 3.D. Supplementary results on the structure of U.S. Cities

#### 3.D.2 Share of Census Tracts with a median income above the UA median income in 2016

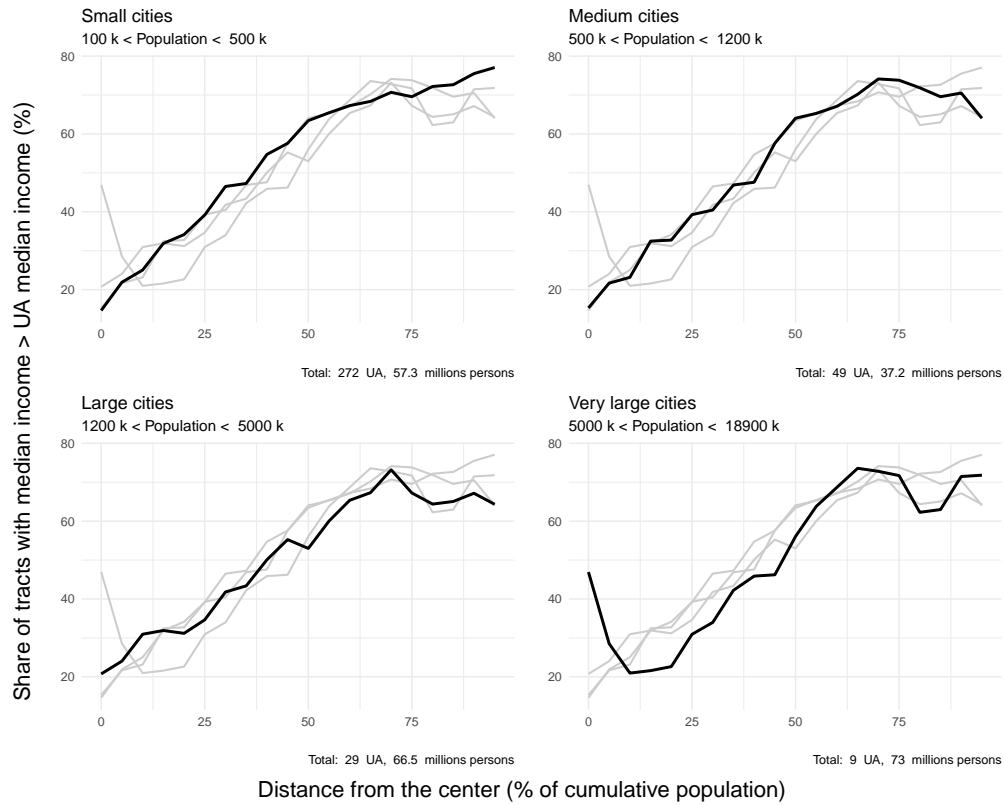


Figure 3.D.2: Share of Census Tracts with a median income above the Urbanized Area median income as a function of distance to the center for UA with different total populations. Source: American Community Survey 2016.

### 3.D. Supplementary results on the structure of U.S. Cities

#### 3.D.3 Evolution of the share of college-educated between 2010 and 2016

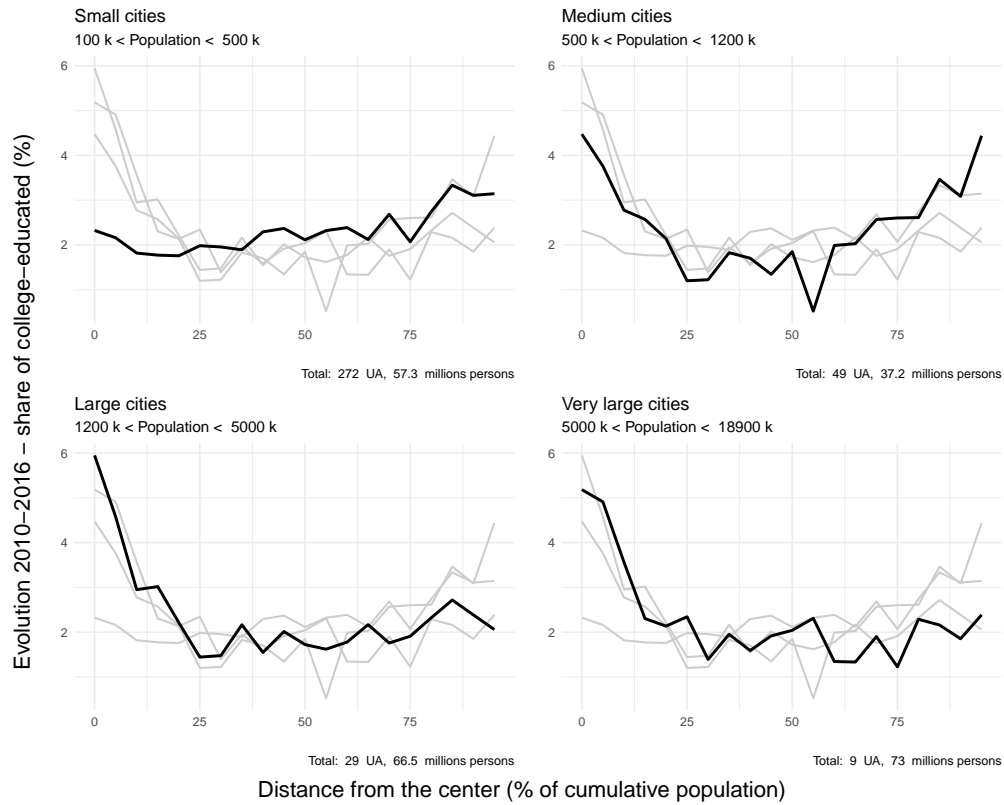


Figure 3.D.3: Differences between 2010 and 2016 in the share of college graduates among population aged between 25 and 64 years as a function of distance to the center, for UA with different total populations. Source: American Community Survey 2010 and 2016.

### 3.D. Supplementary results on the structure of U.S. Cities

#### 3.D.4 Evolution 2010-2016 of share of Census Tracts with a median income above the corresponding Urban Area median income

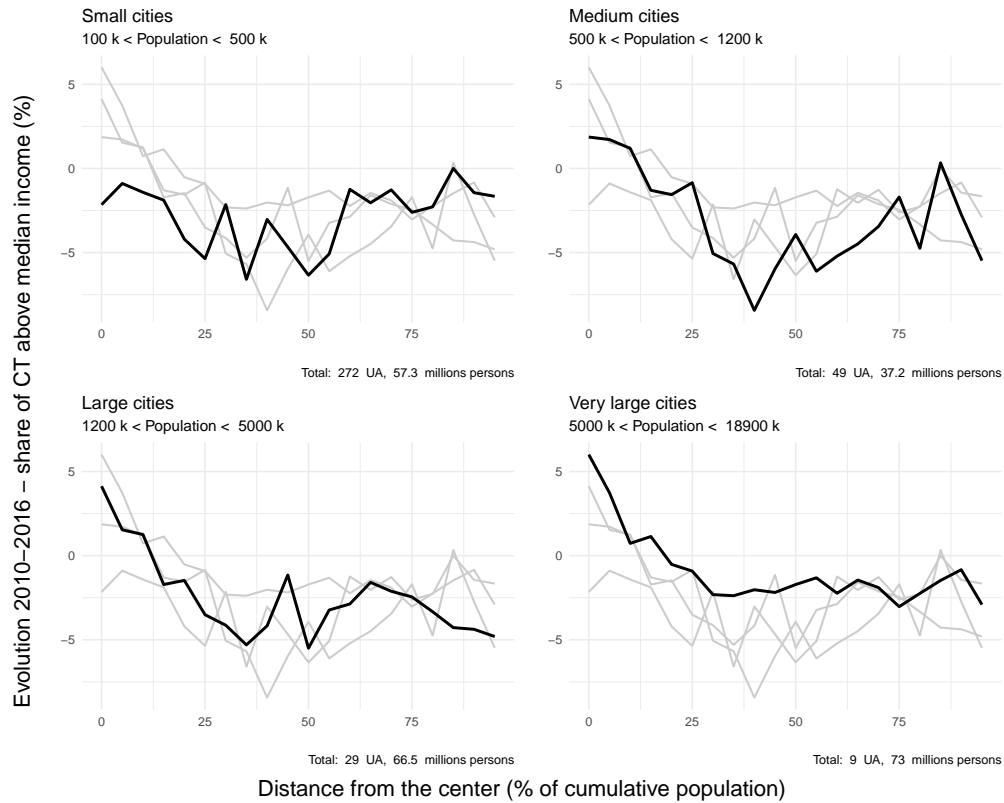


Figure 3.D.4: Differences between 2010 and 2016 in the share of Census Tracts with a median income above the UA median income as a function of distance to the center, for UA with different total populations. Source: American Community Survey 2010 and 2016.

## Chapter 4

# Forecasting transit-induced changes in social composition of neighborhoods: an application to the Grand Paris Express

*There is a great risk that the arrival of the metro and the future arrival of the tramway will drive out the population for whom this equipment was originally designed.*

Patrice Bessac, mayor of Montreuil, a municipality next to Paris<sup>a</sup>

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<sup>a</sup>Quoted by BFMTV, Jan. 8, 2019 (translation our own)

### 4.1 Introduction

During the last decades, Transit-Oriented Development (TOD) has emerged as a powerful paradigm for urban planning, finding a significant echo in local and international institutions. Public transit is regarded as a policy intervention that enhances accessibility and promotes sustainable urban growth. In particular, new infrastructure in low-income neighborhoods can improve access to employment and amenities for residents who may not be able to afford commuting by car. However, the gains in accessibility, capitalized in housing prices, may also lead to the displacement of low-income residents by richer ones. In this case, the benefits for low-income inhabitants may be lower than expected (Pollack et al., 2010). This phenomenon is sometimes referred to as the “affordability paradox of TOD” (Dong, 2017).

The aim of this chapter is to discuss how to anticipate the effects of new rail transit infrastructure on income sorting. Accounting for the relocation of inhabitants can be seen as a necessary step towards assessing the broader distributional impact of public transit.

## 4.1. Introduction

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Subsidizing public transit projects is justified if they generate significant socioeconomic benefits. There has been intensive research on how to provide aggregate measures of such benefits, motivated by the generalization of Cost-Benefit Analysis (CBA) as a rationale for new projects.<sup>1</sup> How the gains are distributed among inhabitants of different social groups remains an open question (see e.g. Di Ciommo and Shiftan, 2017).

Benefits from public transit can be decomposed between: (i) gains in transport times, considering fixed origin-destination trips,<sup>2</sup> and potentially modal shift, (ii) gains in accessibility to employment or amenities for inhabitants, holding residence location fixed,<sup>3</sup>, (iii) gains that come from the “decongestion” of urban land, which leads to the attraction of new residents or industries, and/or a decrease in land prices, and (iv) a decrease in negative externalities from car traffic. Our study aims at providing insights on the distribution of gains of types (ii) and (iii).<sup>4</sup>

We build a partial equilibrium model of location choices with multiple groups of workers. As discussed in section 4.2, previous empirical studies find heterogeneous effects of new public infrastructure on income sorting. This makes it difficult to anticipate the effects of a project. In this study, we consider that public transit innovations provide heterogeneous gains in accessibility because employment opportunities are not evenly distributed in space for workers with different skills or occupations. A transit line that serves an employment area with a high share of skilled jobs, such as a city’s financial district, generates gains in accessibility that are higher for high-skilled workers than for low-skilled ones. In order to formalize this intuition, we embed an Hansen-type accessibility indicator (Hansen, 1959) in an urban economics framework. Previous studies have established that such indicator is a good predictor for property prices or land prices (Osland and Thorsen, 2008; Ahlfeldt, 2011, 2013). We build an accessibility indicator *specific to each group of workers* and we show that it can yield predictions on the social composition of neighborhoods.

The main advantage of the model used here is its simplicity. Hansen-type indicators are easy to compute from local data. The model yields explicit relations between accessibility to employment and neighborhood composition. The functional form we use enables us to estimate directly the parameters of the model. We make use of the successive openings of new rail transit lines between 1968 and 2010 in the Paris region. In total, 34 interventions on the rail network occurred during this period (openings or extensions of lines - see Appendix 4.D). Using a multiple-period time-lag model, we estimate the key parameter of interest, that links changes in accessibility to employment to changes

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<sup>1</sup>See for instance the review of how CBA is used in the United Kingdom by Mackie (2010) and the discussion by Quinet (2010) in the case of France.

<sup>2</sup>See e.g. Bureau and Glachant (2011) who study the distributional effects of transport fare and speed policies in the Paris Region, considering that location and travel behaviours are fixed.

<sup>3</sup>For an example of this approach, see Bocarejo and Oviedo (2012).

<sup>4</sup>Assessing the distribution of the gains of type (iv) is beyond the scope of this work and left for future research.



## 4.1. Introduction

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in municipal residential composition. The underlying assumption is that we are close to quasi-randomization when considering both the geography of transport innovations as well as their sequencing over time, for a sufficient number of transport innovations.<sup>5</sup> For the estimation, we create a unique dataset of reconstituted historical transport times by public transit for the period 1968-2010. We also use historical Census data on neighborhood composition, local housing price data, and origin-destination commuting flows.

This chapter makes two main contributions. First, it contributes to the literature about the impact of public transit on income sorting. Our model rationalizes the fact that public transit innovations yield different effects on income sorting depending on the geography of the transport network. This may explain why previous studies find heterogeneous effects (see our review in section 4.2), depending on the city, the line, or the station considered. Second, the framework we build is used to anticipate the effects of a transit infrastructure currently being built in the Paris region, the Grand Paris Express (GPE). It enables us to disentangle the direct local effects of public transit and the indirect effects due to the equilibrium on the housing market. Further work could expand the present model, in directions that we discuss in section 4.9.

An important limitation of this study is that we consider fixed employment locations for our simulation. That is, we consider that the new transport infrastructure will only marginally alter the overall distribution of employment. This assumption enables us to maintain a limited complexity to our model. In appendix 4.C, we show that, despite multiple transport innovations in the last 40 years, employment distribution has been stable in the Paris region, and that the most important growth in employment can be linked to specific large-scale planning operations, such as the construction of a new airport, a new financial district, or new administrative centers.

The rest of the chapter is organized as follows: section 4.2 discusses the previous literature on public transit and income sorting, section 4.3 presents the context of the GPE and the Paris region, section 4.4 presents the theoretical framework used for the analysis; in section 4.5 and 4.6, we detail the empirical strategy and the data used to test whether the model provides relevant predictions; in section 4.8, we use the model to anticipate the effects of the GPE on the sorting of workers. Finally, we discuss in 4.9 possible extensions of the framework to provide a general estimation about the distributional impacts of public transit policies.

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<sup>5</sup>Most recent papers in transport economics analyze the causal effect of a single infrastructure program, using a difference-and-difference approach. Because “treated” locations main not be randomly chosen, some papers rely on instrumental variables to do so, with IV based on historical routes (Duranton and Turner, 2012), quasi-natural experiments (Donaldson, 2018), or the focus on “in-between” locations (Banerjee et al., 2012; Mayer and Trevien, 2017). Here, we primarily aim at providing out-of-sample predictions and therefore use a structural approach (for a similar general approach, see e.g. Ahlfeldt, 2013).

## 4.2 Public transit and income sorting

There is growing evidence that transport infrastructure shape the spatial organization of cities. Previous literature has emphasized the effects of public transit on urban sprawl and population suburbanization (Burchfield et al., 2006; Mayer and Trevien, 2017; Gonzalez-Navarro and Turner, 2018), on employment decentralization (Garcia-López et al., 2017), on road congestion (Anderson, 2014; Adler and van Ommeren, 2016), or on air pollution (Chen and Whalley, 2012; Gendron-Carrier et al., 2018). An important number of studies document the impacts of newly developed transport infrastructure on local property prices in the short term (e.g. Baum-Snow and Kahn, 2000; Lin, 2002; Gibbons and Machin, 2005). Debrezion et al. (2007) provide a meta-analysis of this literature. In a paper about the extension of London’s transit system, Ahlfeldt (2013) uses a model where workers value accessibility to employment. The model is estimated on previous openings of transit lines and used to predict the impacts of future lines on property prices. Such a prediction is of particular interest when considering land value capture as a tool to finance the infrastructure.

Our analysis builds on the contribution by Ahlfeldt (2013), but focuses on the effects of public transit on the sorting of population. Existing literature gives contradictory predictions of the effects of public transit on income sorting. On the one hand, LeRoy and Sonstelie (1983) argue that high-income workers favor high speed modes, such as private cars, while low-income workers favor cheap modes, such as public transit. Because public transit is not evenly spatially distributed, it may impact the sorting of inhabitants based on income. Based on this theory, Glaeser et al. (2008) highlight the role of public transportation in explaining the poverty of US city centers (see also Pathak et al., 2017).

On the other hand, Bardaka et al. (2018) provide evidence that new light rail systems in Denver increased households’ income close to the stations. In the Paris region, Mayer and Trevien (2017) find that municipalities crossed by new suburban trains attracted more college graduates.<sup>6</sup>

Other studies find heterogeneous results. In a study over 14 US cities, Kahn (2007) finds that neighborhoods close to new “walk and ride” stations experienced an increase in the share of college graduates after the opening of the lines, while ones close to “park and ride” stations did not. Grube-Cavers and Patterson (2015) show a significant positive relationship between transit exposure and gentrification in Montreal and Toronto, but no significant relationship for Vancouver. Dong (2017) finds no overall effect of new rail-public transit on gentrification in suburban Portland, but finds local effects for specific lines.

Overall, previous empirical literature finds either ambiguous or heterogeneous effects of public transit on income sorting. It does not seem possible to infer from a literature

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<sup>6</sup>We focus on studies that look explicitly at the composition of neighborhoods. Other studies, such as Lin (2002), use property prices as indicators for gentrification. However, we do not consider that an increase in property prices is necessarily associated with gentrification.

### 4.3. The gentrification of Paris

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review that a transit project will, or will not, induce gentrification. New tools are therefore required for anticipation. This chapter aims at contributing to this objective. In particular, the model we develop rationalizes why different public transit projects can have different effects on income sorting.

### 4.3 The gentrification of Paris

In what follows, we apply our model to anticipate the effect of a specific transit infrastructure, the GPE. The GPE project mainly serves the inner suburbs of Paris (see the map of figure 3), where accessibility by public transit has long been significantly lower than in the central city. Inner suburbs remain the area of residence of a significant share of middle- and low-income workers of the metropolitan area, but are experiencing social changes that seem to prolong past trends.

**Evolution of income sorting in the Paris region (1968-2015)** We use census data to document changes in the Paris region between 1968 and 2015. Harmonized census data gives us the municipality of residence of employed workers aged between 25 and 54<sup>7</sup>, distinguishing their occupational categories. As argued in section 4.B, occupational categories can be used as a first order proxy for income groups. On figure 1, we represent the changes in residence location distribution as a function of distance to the center and occupational category. The curves in Figure 1 were all normalized to 1 to show only relative locations. For all the figures, the distributions have all flattened between 1968 and 2015, reflecting the fact that the growth of the urban area has been more “horizontal” than “vertical”. However, the sprawl has not been homogeneous across groups. The distribution of residence locations for high-income workers has remained similar between 1968 and 2015, while more differences are observed for middle- and low-income workers. In 2015, around 33% of workers from high-income occupational categories lived within 5 km of the city center (*Hôtel de Ville*), compared to 37% for 1968. This share was 22% for low-income occupational category, while it was 35% in 1968. On average, the lower the income of the occupational category, the further away from the center have workers moved.

This led to changes in the composition of local population. On figure 2, we represent the changes in the composition of each ring of distance to the center. Between 1968 and 2015, the number of workers of high-income occupational categories was multiplied by almost 3 (from 500,000 to 1.5 millions). As a consequence, the composition of the population in central Paris changed dramatically. In 1968, around 500,000 workers of low-income occupational categories lived in the municipality of Paris (“central city”)<sup>8</sup>

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<sup>7</sup>The advantage of this data set is that historical comparability is guaranteed by the French statistical institute (INSEE), who built this data set. See section 4.6 for a more detailed presentation.

<sup>8</sup>In practice, the municipality of Paris only represents the central part of the metropolitan area of Paris, which is better approximated by the region Ile-de-France.

### 4.3. The gentrification of Paris

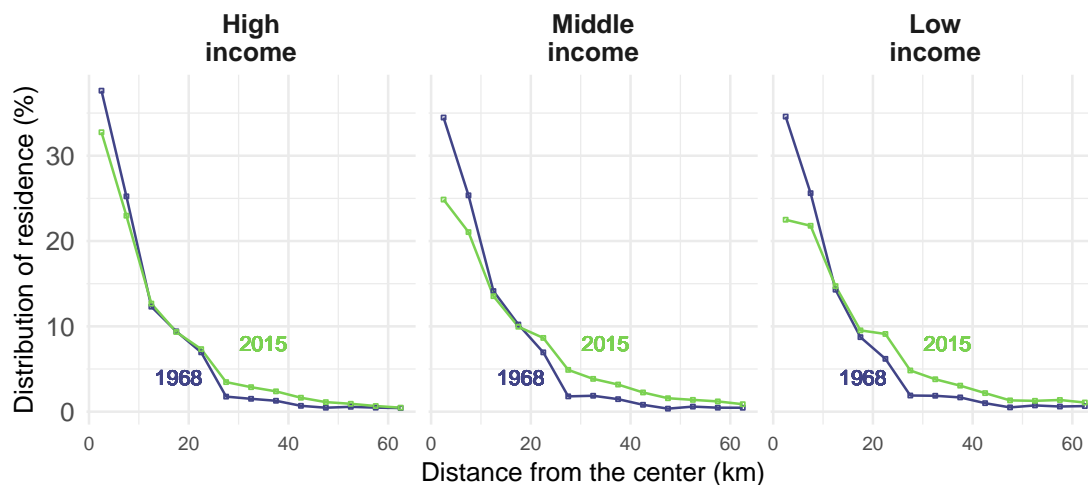


Figure 1: Distribution of residence locations as a function of distance to the center for workers of different occupational categories.

Sample includes all employed workers aged 25-54 in 1968 and 2015. The center of Paris was defined as the *Hôtel de Ville*. A bin width of 5 km was used. See Appendix 4.B for the definitions of low-, middle-, and high-income categories. Source: Census, 1968-2015.

In 2015, there were half this number. During the same period, their number in outer suburbs increased by around 300,000.

In this context, one can wonder whether future growth in the number of high-income categories workers will lead to a replacement of the low-income ones in the inner suburbs, as it did in the central city. The ongoing trend of gentrification in some municipalities of the “first ring” around Paris, that started before the GPE was announced, is well documented (see e.g. Préteceille, 2007; Jabot et al., 2019). In this context, the project of the GPE has raised early concerns about its impact on gentrification (Enright, 2013).

**Evolution of public transport in the Paris region** Did previous extensions of the public transit network play a role in these changes? Between the 1960s and today, the transit system in the Paris metropolitan area improved significantly. The Réseau Express Régional (RER) is arguably the most important project completed during this period. For this project, several train lines were merged into 5 high-capacity lines, leading to significant gains in accessibility for suburban municipalities.<sup>9</sup> The RER project had significant impacts on employment decentralization, population growth, and composition in the municipalities served (Garcia-López et al., 2017; Mayer and Trevien, 2017). In particular, Mayer and Trevien (2017) show that the population growth for skilled workers was greater than for non-skilled workers in municipalities crossed by the RER.<sup>10</sup>

<sup>9</sup>We invite the reader to refer to Garcia-López et al. (2017) and Mayer and Trevien (2017) for a detailed presentation of the RER project and the gains in accessibility that it provided.

<sup>10</sup>This conclusion holds mostly for municipalities in the inner suburbs because of their choice of instrumental variable.

#### 4.4. Model

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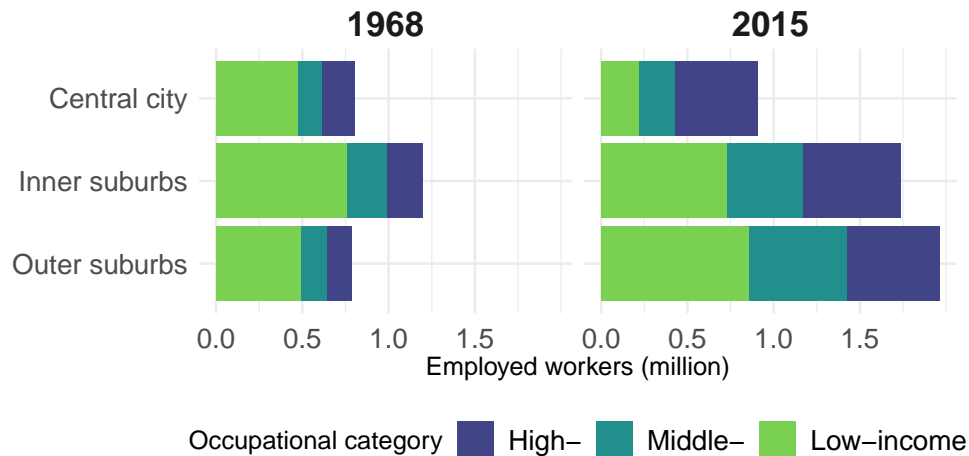


Figure 2: Number of employed residents per employment category and ring of distance from Paris center in 1968 and 2015.

Sample includes all employed workers aged 25-54 in 1968 and 2015. “Central city” represents the municipality of Paris. “Inner suburbs” include the three *Départements* around Paris. “Outer suburbs” are the rest of the Paris region. Source: Census, 1968-2015.

In the empirical section of this chapter, we consider all extensions of the rail public transit network between 1968 and 2010. Those include the 5 new RER lines, but also one new metro line (line 14), the extension of 7 metro lines, 2 new tram lines, and the creation of lines as part of the “Transilien” network (long-range suburban trains). In what follows, we show that gains in accessibility induced by those extensions can be linked to changes in the local composition of the population.

#### 4.4 Model

We develop a model of intra-metropolitan location where workers choose their residence as a function of accessibility to jobs. The model builds on three strands of literature. First, workers choose their location of residence by considering a trade-off between accessibility and affordability, in line with the urban economics literature following Alonso (1964). Our specifications for utility and bid-rents are similar to Ahlfeldt (2013). Second, we introduce multiple groups of workers and group mixing, following the random bid-rent approach from Ellickson (1981). Finally, we build a dynamic framework for the empirical work, by considering a timelag in the adjustment of population to the equilibrium, following a standard approach in the “Carlino-Mills” models of residence locations (Carlino and Mills, 1987; Boarnet et al., 2005; Bollinger and Ihlanfeldt, 1997).

## 4.4. Model

### 4.4.1 General framework

The city is composed of  $I$  residence locations, indexed by  $i$ . The workers residing there are divided into  $G$  groups, indexed by  $g$ , according to the type of job they hold.<sup>11</sup>

We assume that workers of type  $g$  living in  $i$  derive utility from consumption of a composite good  $z_{ig}$ , consumption of housing  $q_{ig}$ , accessibility to employment  $a_{ig}$ , and local amenities  $b_{ig}$ . We assume that utility is a Cobb-Douglas function of these attributes:

$$u_{ig} = z_{ig}^\alpha q_{ig}^\beta a_{ig}^\gamma b_{ig}^\delta \quad (4.1)$$

with  $\alpha + \beta = 1$  (housing and composite good are the only goods that intervene in the budget constraint). The cost of the composite good is set to 1. Housing consumption and price are endogenous. We assume that monetary costs of transport are constant across locations, that is their variable part is small compared to the fixed cost and can be neglected, as in Ahlfeldt (2011).<sup>12</sup> Therefore, workers of group  $g$  have a fixed budget  $w_g$ , which corresponds to the income net of fixed commuting costs, and allocate it on composite goods and on housing. The budget constraint is:  $w_g = z_{ig} + q_{ig}\psi_{ig}$ , where  $\psi_{ig}$  is the bid-rent per unit of housing. First order condition gives:

$$\begin{cases} q_{ig} &= \beta \frac{w_g}{\psi_{ig}} \\ z_{ig} &= \alpha w_g \end{cases} \quad (4.2)$$

The spatial equilibrium condition implies that the utility of workers from group  $g$  must be constant across locations, that is:  $u_{ig} = u_g$ . The bid-rent is therefore:

$$\psi_{ig} = \left[ \alpha^\alpha \beta^\beta \frac{w_g}{u_g} \right]^{\frac{1}{\beta}} a_{ig}^{\frac{\gamma}{\beta}} b_{ig}^{\frac{\delta}{\beta}} \quad (4.3)$$

Under standard assumption ( $0 < \alpha, \beta, \gamma, \delta$ ), the bid-rent is higher in locations with higher accessibility to employment and higher amenities. Higher wage and lower utility also increase the bid-rent.

In each location  $i$ , the total supply of housing in terms of floorspace is assumed to be exogenous, and denoted  $S_i$ . Workers compete for housing. In standard urban economics models, housing is allocated to the group (or the use) with the highest bid-rent, which leads to a totally segregated city, with no mixing between income groups. In practice, a city such as Paris is far from being completely segregated. We introduce group mixing using the stochastic bid-price approach introduced by Ellickson (1981). We assume that

<sup>11</sup>In what follows,  $g$  refers to occupational categories. However, the model could be applied with, for example, industry of employment, educational attainment, or income group.

<sup>12</sup>Neglecting the monetary cost of transport may be a strong assumption, as it can represent a minor yet significant share of the estimated generalized costs (Van Ommeren and Dargay, 2006; Small et al., 2007; Duranton and Puga, 2014). However, the role played by the *variable* part in the transport costs is likely to be smaller, as fixed costs are important (the fixed share for a public transit ticket, the purchase and insurance cost for a car). As we will discuss in section 4.9, extensions of our model that account for multiple modes and their monetary costs are possible.

#### 4.4. Model

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a landlord  $l$  renting out to a household from group  $g$  perceives a log-utility  $\log(\psi_{ig}) + \epsilon_l$ , where the  $\epsilon_l$  follow a Gumbel-max law of parameter  $1/\mu$ . The random part that guides the landlord choice is a black box approach, that encompasses imperfect information, historical inertia or idiosyncratic preferences from landlords. Utility maximization by landlords leads to the share of the floorspace in  $i$  that is allocated to workers of group  $g$ , denoted  $\sigma_{ig}$ . Following McFadden (1974), it writes as a “logit” equation:

$$\sigma_{ig} = \frac{(\psi_{ig})^\mu}{\sum_{h=1}^G (\psi_{ih})^\mu} S_i \quad (4.4)$$

Note that in the limit case where  $\mu = +\infty$ , floorspace is entirely allocated to the group with the highest bid-rent. If  $\mu = 0$ , there is a perfect mixing of groups everywhere in the city. The number of workers of group  $g$  living in  $i$  is equal to the floorspace allocated to group  $g$  divided by the bid-dwelling size, that is:  $n_{ig} = \sigma_{ig}/q_{ig}$ . Combining (4.2) and (4.4), we get:

$$n_{ig} = \frac{(\psi_{ig})^{\mu+1}}{\sum_{h=1}^G (\psi_{ih})^\mu} \frac{S_i}{\beta w_g} \quad (4.5)$$

##### 4.4.2 Effect of a public transit innovation

The framework described above can be used to anticipate the effect of a change in the transport network on the relative location of workers. Here, we derive the marginal effect of the public transit *all else being equal*. To derive equations (4.6), (4.7) and (4.8), we assume that the transport project does not alter the location of jobs, the wages for each group  $g$ , the local value of amenities, nor the supply of floorspace.<sup>13</sup> Consequently, only  $a_{ig}$  and  $u_g$  are expected to change.

We denote with the superscript  $P$  a variable in the equilibrium situation with a new transport project built, all else being equal. Following (4.3), the ratio of bid-rents between the situation with and without the transport project is:

$$\frac{\psi_{ig}^P}{\psi_{ig}} = \left( \frac{a_{ig}^P}{a_{ig}} \right)^{\frac{\gamma}{\beta}} \left( \frac{u_g^P}{u_g} \right)^{-\frac{1}{\beta}} \quad (4.6)$$

The increase in bid-rents is higher in locations where the increase in accessibility is higher. For each group  $g$ , the second term is a function of the overall change in utilities. As discussed below, the model can be used both in the “open” city case, for which the utility is unchanged by the project, and in the “closed” city case. In the open city case, an increase in accessibility increases bid-rents with an elasticity of  $\gamma/\beta$ . In the closed city case, we adjust the utilities in order to keep the population of each group constant. Therefore, there is an adjustment in the overall level of bid-rents due to changes in utility.

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<sup>13</sup>Further work could try and go beyond these assumptions. We discuss the location of jobs in section 4.9. In particular, introducing endogenous supply of housing floorspace would be relatively simple. The interaction between public transit and amenities appears to be more complex.

## 4.5. Empirical strategy

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Because of this utility effect, the transport project may lead to a decrease in bid-rents in the locations where the gain in accessibility is low (even though it is positive).

Using (4.5), we compute the ratio of the number of workers of group  $g$  living in  $i$ :

$$\frac{n_{ig}^P}{n_{ig}} = \left( \frac{a_{ig}^P}{a_{ig}} \right)^{\frac{\gamma}{\beta}(1+\mu)} \left( \frac{u_g^P}{u_g} \right)^{-\frac{(1+\mu)}{\beta}} \left( \frac{\sum_h (\psi_{ih}^P)^\mu}{\sum_h (\psi_{ih})^\mu} \right)^{-1} \quad (4.7)$$

The values of  $\psi_{ik}^P$  and  $\psi_{ik}$  are *a priori* unknown. Using equations (4.5) and (4.6), we get a formula that does not depend on the bid-rents (detailed calculations can be found in Appendix 4.A):

$$\begin{aligned} \log \frac{n_{ig}^P}{n_{ig}} = & \underbrace{\frac{\gamma(1+\mu)}{\beta} \log \left( \frac{a_{ig}^P}{a_{ig}} \right)}_{\text{(i) group-location-specific increase in accessibility}} - \underbrace{\frac{(1+\mu)}{\beta} \log \left( \frac{u_g^P}{u_g} \right)}_{\text{(ii) group-specific equilibrium effect (closed city only)}} \\ & - \underbrace{\log \left( \frac{\sum_h \left( \frac{a_{ih}^P}{a_{ih}} \right)^{\frac{\gamma\mu}{\beta}} \left( \frac{u_h^P}{u_h} \right)^{-\frac{\mu}{\beta}} (n_{ih}w_h)^{\frac{\mu}{1+\mu}}}{\sum_h (n_{ih}w_h)^{\frac{\mu}{1+\mu}}} \right)}_{\text{(iii) location-specific equilibrium effect}} \end{aligned} \quad (4.8)$$

This equation gives the ratio between the equilibrium population in two equilibria, assuming wages, amenities, and local supply of housing are equal. The first term corresponds to a local, group-specific gain in accessibility. The second term corresponds to group-specific equilibrium effects. This term does not intervene in the open city case, but in the closed city case, there can be a decrease in the number of workers in locations where the gains in accessibility are low (compared to the other locations). The third term in equation (4.8) is a location-specific effect. Because of this term, there can be a decrease in the number of workers of a group  $g$  if the local gains in accessibility are comparatively greater for other groups.

Whether a new transport system increases the number of workers of a group  $g$  in location  $i$  thus depends on (i) how it increases accessibility for workers of *this group* in *this location*, (ii) how this gain in accessibility compares to gains in accessibility for *this group* in *other locations*, and (iii) how this gain in accessibility compares to gains in accessibility for workers of *other groups* in *this location*. Changes in the composition of neighborhood are therefore *a priori* unknown and depends on the actual gains in accessibility provided for each group, which are determined by the geography of the line (in relation to the geography of jobs).

## 4.5 Empirical strategy

The empirical strategy has two purposes. First, we show that previous changes in the composition of neighborhood can be linked to changes in the transport network, following



## 4.5. Empirical strategy

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the mechanisms integrated in our framework. Second, we identify plausible values for the key parameters of our model. In practice, three parameters guide the quantitative predictions of our model. First, the model is sensitive to the functional form chosen for accessibility to employment, and the parameter(s) associated with it. Second, the ratio  $\gamma/\beta$ , that is the elasticity of indirect utility with respect to accessibility to jobs, drives the impact of accessibility on bid-rents. Third, the parameter  $\mu$  drives the impact of changes in bid-rents on changes in population composition. Therefore, the empirical strategy is divided in three parts. We give particular attention to the third part, which has not to our knowledge been studied before.

### 4.5.1 Defining accessibility to employment

We choose a definition of accessibility that follows Ahlfeldt (2013), here applied to multiple groups. We define accessibility as the sum of the number of jobs, weighted by an origin-destination matrix:

$$a_{ig} = \sum_c E_{cg} C_{ic} \quad (4.9)$$

where  $E_{cg}$  is the number of jobs of type  $g$  in employment location  $c$  and  $C_{ic}$  is the commuting cost matrix that represents the weight of employment center  $c$  relatively to  $i$ . We assume that  $C_{ic}$  is independent of group  $g$ , that is workers from different groups get the same decay in utility for a given transport time. We assume this decay function follows a negative exponential form:

$$C_{ic} = \exp(-\tau t_{ic}) \quad (4.10)$$

where  $t_{ic}$  is the transport time between  $i$  and  $c$  and  $\tau$  is the spatial decay parameter.

With this specification, the differences of accessibility between groups is only driven by differences in the location of employment opportunities. In practice, there exists significant variations in employment composition between municipalities in the Paris region. In section 4.8, we show for instance that the share of jobs occupied by high-income occupational categories range between less than 10% and more than 50%, with the highest share observed in the financial district (*La Défense*).

In order to estimate the parameter  $\tau$ , we consider that the spatial weight matrix is proportional to the probability for a worker living in  $i$  to accept a job located in a center  $c$ . We follow the same methodology as Ahlfeldt et al. (2015) to retrieve the spatial decay parameter, by estimating a semi-log equation for commute flows between pairs of municipalities:

$$\log(\phi_{ic}) = -\tau t_{ic} + \mu_i + \kappa_c + \epsilon_{ic} \quad (4.11)$$

where  $\phi_{ic}$  is the flow of commuters between location  $i$  and employment center  $c$ ,  $t_{ic}$  is the transport time, and  $\mu_i$  and  $\kappa_c$  are origin and destination fixed-effects that capture the sizes of residence and workplace locations.

## 4.5. Empirical strategy

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### 4.5.2 Hedonic price model

We derive a hedonic price model to determine the price-elasticity of accessibility to employment. Two difficulties limit the scope of this model. First, we cannot retrieve group-specific bid-rents, as our data set on transaction does not include information on the buyers. We therefore use in the regressions a measure of accessibility to employment that is not group-specific and encompasses all jobs. Second, housing value data are not available over a long enough historical period. We therefore estimate the parameter  $\gamma/\beta$  using cross-section data. The estimated hedonic model is:

$$\log(P_n) = \sum_j \alpha_j h_{jn} + \frac{\gamma}{\beta} \log(a_i) + \sum_k \rho_k \zeta_{ik} \quad (4.12)$$

where  $P_n$  is the price of the property  $n$ ,  $h_{jn}$  is the value of the attribute  $j$  of the property  $n$ ,  $\alpha_j$  is the valuation of attribute  $j$ ,  $a_i$  is the accessibility to employment from the municipality  $i$  where the property  $n$  is located,  $\zeta_{ik}$  is the value of amenity of type  $k$  in  $i$ , and  $\rho_k$  is the valuation of amenity of type  $k$ .

As robustness checks, we also use average prices and rents per municipality (see section 4.6). In this case, the regression does not include property-level variables.

### 4.5.3 Effect of changes in accessibility on the composition of neighborhoods

The second part of the empirical analysis consists in studying the impact of accessibility to employment on the composition of neighborhoods. Accessibility to employment is a function of (i) job locations and (ii) transport times between locations. Because of the potential simultaneity of the location of workplaces and residences, there is a strong endogeneity issue with (i). As a result, cross-section regressions may be biased. We therefore identify the effect of changes in accessibility to employment over time, due only to improvement in the transport system, on the changes in the composition of neighborhoods. Because such changes may be slow, we derive a time-lag model and incorporate inertia, following the specification from Carlino and Mills (1987).

Using the expression for bid-rents in equation (4.3), we obtain the following log-linear expression for the equilibrium number of workers of type  $g$  living in  $i$ :

$$\log(n_{ig}) = \bar{\mu}_1 \log(a_{ig}) + \bar{\mu}_2 \log(b_{ig}) + \nu_i + \theta_g \quad (4.13)$$

where  $\bar{\mu}_1 = (\mu + 1)\gamma/\beta$ ,  $\bar{\mu}_2 = (\mu + 1)\delta/\beta$ ,  $\nu_i = \log(S_i) - \log(\sum_{h=1}^G (\psi_{ih})^\mu)$ , and  $\theta_g = \log(\alpha^\alpha w_g^{\alpha/\beta}/u_g)$ . Note that  $\nu_i$  only depends on the location  $i$  and  $\theta_g$  only depends on the group  $g$ .

Following Carlino and Mills (1987), we assume that population adjusts to the equilibrium with a time lag. The observed change in log-population between  $t - 1$  and  $t$

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is:<sup>14</sup>

$$\Delta_t \log(\bar{n}_{ig}) = \lambda(\log(n_{ig,t}) - \log(\bar{n}_{ig,t-1})) \quad (4.14)$$

where  $\bar{n}$  is the observed population and  $\Delta_t x$  denotes the evolution of a variable  $x$  between dates  $t-1$  and  $t$ . Because this equation represents a phenomenon of inertia, the time-lag parameter  $\lambda$  should be between 0 and 1.

Combining equations (4.13) and (4.14), we write the observed change in log-population as a function of lagged explanatory variables:

$$\begin{aligned} \Delta_t \log(\bar{n}_{ig}) = & \bar{\mu}_1 \lambda \Delta_t \log(a_{ig}) + \bar{\mu}_1 \bar{\lambda} \Delta_{t-1} \log(a_{ig}) + \bar{\mu}_1 \bar{\lambda} \log(a_{ig,t-2}) \\ & + \bar{\mu}_2 \lambda \Delta_t \log(b_{ig}) + \bar{\mu}_2 \bar{\lambda} \Delta_{t-1} \log(b_{ig}) + \bar{\mu}_2 \bar{\lambda} \log(b_{ig,t-2}) \\ & - \bar{\lambda} \log(\bar{n}_{ig,t-2}) + \nu_{it} + \theta_{gt} \end{aligned} \quad (4.15)$$

where  $\bar{\lambda} = \lambda(1 - \lambda)$ . This equation links changes in the composition of a neighborhood (left-hand side) to changes in group-specific accessibility and group-specific amenities (right-hand side). The key parameter of interest for this estimation is  $\bar{\mu}_1 = (\mu + 1)\gamma/\beta$ , associated with changes in accessibility.

Because our aim is to identify the effect of public transit, we consider that amenities serve as control variables.<sup>15</sup> We assume that there are  $K$  types of amenities in the city. In each location, there is a quantity  $\zeta_{ik}$  of amenities of type  $k$ . Workers from different groups value differently amenities, and this valuation may change over time. We define the group-specific amenity score  $b_{ig}$  as:

$$b_{ig} = \prod_{k=1}^K (\zeta_{ik})^{\rho_{gk}} \varepsilon_{ig} \quad (4.16)$$

where  $\varepsilon_{ig}$  represents a random group-location specific term, assumed to follow a log-normal law. The evolution of  $\log(b_{ig})$  can therefore be approximated by the following expression:

$$\Delta_t \log(b_{ig}) \approx \sum_k \log(\zeta_{ik,t-1}) \Delta_t \rho_{gk} + \sum_k \rho_{gk,t-1} \Delta_t \log(\zeta_{ik}) + \epsilon_{igt} \quad (4.17)$$

where  $\epsilon_{igt}$  follow a normal law. Similarly, because of the issues of endogenous amenities, we only include in the regression the value of amenities at the initial date. This implies to keep from equation (4.17) only the term reflecting the changes in the valuation of amenities. This assumption is supported by Couture and Handbury (2017), which argue that the changes in the valuation of amenities are the main drivers of recent gentrification of city centers in the United States (US).

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<sup>14</sup>Note that a difference with the model from Carlino and Mills (1987) is that we consider that the lag applies log-linearly, while they use a linear form. The qualitative intuition remains the same.

<sup>15</sup>Note, however, that the same framework could be used to assess quantitatively the impact of changes in specific amenities on the sorting of inhabitants.

## 4.6. Data

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We therefore estimate the following equation:

$$\begin{aligned} \Delta_t \log(\bar{n}_{ig}) = & \alpha_1 [\Delta_t \log(a_{ig})]_{\text{trans}} + \alpha_2 [\Delta_{t-1} \log(a_{ig})]_{\text{trans}} + \alpha_3 \log(a_{ig,t-2}) \\ & - \alpha_4 \log(\bar{n}_{ig,t-2}) + \sum_k \rho_{gkt} \zeta_{ik,t-2} + \nu_{it} + \theta_{gt} + \tilde{\varepsilon}_{igt} \end{aligned} \quad (4.18)$$

where  $\zeta_{ik,t-2}$  is the initial value of amenity  $k$ ,  $\rho_{gkt}$  is the group- and period-specific change in the valuation of this amenity.  $\nu_{it}$  and  $\theta_{gt}$  are location-period and group-period specific fixed effects.  $[\Delta_t \log(a_{ig})]_{\text{trans}}$  and  $[\Delta_{t-1} \log(a_{ig})]_{\text{trans}}$  are the changes in log-accessibility to employment due to changes in transport times, keeping initial employment locations fixed, that is:

$$\begin{aligned} [\Delta_t \log(a_{ig})]_{\text{trans}} &= \log \sum_c E_{cg,t-2} C_{ic,t} - \log \sum_c E_{cg,t-2} C_{ic,t-1} \\ [\Delta_{t-1} \log(a_{ig})]_{\text{trans}} &= \log \sum_c E_{cg,t-2} C_{ic,t-1} - \log \sum_c E_{cg,t-2} C_{ic,t-2} \end{aligned}$$

## 4.6 Data

We use five main types of data: (i) workplace and residence locations by occupational category between 1968 and 2010, (ii) detailed data about commuting patterns in 2010, (iii) simulated values of transport times by public transit and car between locations, (iv) housing prices and rents in 2010 and 2015, and (v) values for local amenities.

The geographical unit of analysis for this work is the municipality (*communes*). Municipalities were stable in the Paris region over the period 1968-2015. They are 1,300 municipalities in the Paris Region (*Ile-de-France*), including the 20 *arrondissements* of the municipality of Paris, and 431 in the Urban Area of Paris as of 2010.<sup>16</sup>

We derive the number of employed workers per municipality of residence and per municipality of workplace between 1968 to 2015 from standardized historical Census data.<sup>17</sup> The French statistical institute (INSEE) restricted the sample to workers aged 25 to 54 for the data to be comparable over years. It distinguishes 6 occupational categories.<sup>18</sup> A definition of French occupational categories is provided in Appendix 4.B. The definition of occupational categories has been stable over the period considered. Figure 4.B.1 shows the distribution of income by occupational category for the Paris region in 2010. The differences between the distributions suggest that occupational categories can be used as a first order proxy for income groups.<sup>19</sup> We remove ‘‘Farmers’’ from the sample as they represent a negligible share of employed workers in the Ile-de-France Region.

<sup>16</sup>The French national statistical institute INSEE defined Urban Areas (*Unité urbaine*) as an area with a continuity of urban land use.

<sup>17</sup>Census information is available for the census years: 1968, 1975, 1982, 1990, 1999, 2010 and 2015.

<sup>18</sup>*Catégories Socio-Professionnelles* in French.

<sup>19</sup>In particular, we define in appendix 4.B an aggregation in three income groups: ‘‘low-’’, ‘‘medium-’’, and ‘‘high-income’’.

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We also use a detailed file from the Census 2010 to retrieve the commuting flows between municipalities. This dataset contains  $> 1.9$  millions weighted individual-level observations in the Paris region, with the municipality of residence and the workplace municipality. It also includes information about the employment status, the occupational category, and the principal transport mode used.

We compiled a unique data set of historical transport times by public transit between pairs of municipalities, between 1968 and 2010. To do so, we used the infrastructure of the MODUS transport model, a 4-step model developed by the regional administration in charge of environment and planning (DRIEA).<sup>20</sup> This model includes a detailed representation of the public transit network as of 2010 with the location of stations, the transport times between stations, the routes and the connections between lines. We use a shortest-path algorithm to compute the travel times by public transit between each pairs of municipalities, given all the available public transit routes. In order to retrieve transport times in the past, we build a database consisting of all rail line openings between 1968 and 2010, presented in appendix 4.D. We depart from the transit network of 2010, and we approximate the transit network in the previous census years by removing the stops, segments of routes, or entire lines, that were not open at the times. We are then able to compute the minimum transport time between all pairs of municipalities. This corresponds to an approximation of reality, as we do not consider changes in the frequency, nor regularities, of trains. Moreover, we assume that the bus lines remained unchanged during this period. As an example of outputs, figure 4.D.1 of appendix 4.D presents the changes in transport times between all municipalities and the center of Paris between 1968 and 2010.

We also compute the transport time by car between pairs of municipalities using the MODUS model. The 4-step model accounts for congestion on the roads. The simulation was made for the reference year of 2010. We assume that transport times by car remained constant during the period under scrutiny. The underlying assumption is that investments in the road network were made in order to absorb growing traffic and maintain the same times between origins and destinations. The transport times we use in our computation of accessibility to employment is the minimum of transport times between public transit and car, that is:

$$t_{ic} = \min(t_{ic}^{VP}, t_{ic}^{PT}) \quad (4.19)$$

In order to estimate the hedonic model, we make use of two datasets for housing value. First, we use DVF, a national dataset with geocoded information on all property transactions in 2015. This dataset includes the transaction price and only a limited number of property characteristics: the type (apartment/house), the built surface, the land surface for houses, and the number of rooms. The dataset consists of 177,800

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<sup>20</sup>The institution in charge of implementing the GPE (*Société du Grand Paris*) considers the MODUS model as their reference for socioeconomic evaluations. For other academic works that use this model, see e.g. Inoa et al. (2015), Coulombel et al. (2018) and Coulombel et al. (2019)

## 4.7. Results

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observations, when restricted to direct sales in the Paris Region. We also use a second dataset which consists of average rents and transaction prices per square meter for each municipality, scraped from the website [lacoteimmo.com](http://lacoteimmo.com)<sup>21</sup>. This website is edited by seLoger.com, one of the leading housing classified advertisements website in France. We retrieve monthly information<sup>22</sup> at the municipal level for the Paris region.

In order to control for the evolution of amenities, we use data from multiple sources. The control variables considered include (i) natural amenities, including elevation, land uses; (ii) infrastructure (dis)amenities, including the proximity to airport or large transport infrastructure; and (iii) the local housing types and occupation status. Variables and sources are presented in appendix 4.E.

## 4.7 Results

As presented in section 4.5, we estimate three key parameters. In section 4.7.1, we estimate the value of the spatial decay parameter  $\tau$ . Section 4.7.2 presents results for the value of  $\beta/\gamma$ . Finally, in section 4.H, we estimate  $\bar{\mu}_1 = (\mu + 1)\gamma/\beta$ , which enables us to recover the value of  $\mu$ .

### 4.7.1 Results for the gravity equation estimation

Table 1 presents the results of the estimation of equation (4.11). We restrict the sample to positive commuting flows within the Urban Area as of 2010 made by walking or public transportation. Transport times are expressed in minutes. In column (1), we selected all the non-zero commuting flows, while in columns (2)-(4), we restricted the sample to flows greater than 10 commuters. In column (1), we find a value of the elasticity of commuting flows to transport times of  $-0.064$ . The interpretation of this result is that an increase of 1 minute in transport times leads to a decrease of  $1 - \exp(-\tau) \approx 6.2\%$  in the number of commuters. In column (2), we restrict the sample to flows larger than 10 commuters, for which we find a coefficient of  $-0.069$ . The values from column (1) and (2) are close to spatial decay parameters of around 0.09 for the Rosaland region from Osland and Thorsen (2008), 0.05 for London from Ahlfeldt (2013), and 0.07 for Berlin from Ahlfeldt et al. (2015). In columns (3) and (4), the same method is applied but with a restriction to high-income (column 3) and low-income (column 4) occupational categories. We find values that are close, although results suggest that the spatial decay is higher for low-income workers. Overall, the semi-log form is able to reproduce a significant part of the variance of the commuting flows, as suggested by the  $R^2$  coefficients, all above 0.9.

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<sup>21</sup>The reader may find an example of page with rent and price information at this address: <https://www.lacoteimmo.com/prix-de-l-immo/location/ile-de-france/paris/paris-1er/750101.htm>

<sup>22</sup>For the year 2010, for which we have the reference transport time simulation, the website only includes the last three months of the year.

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Table 1: Results from the gravity model

| <i>Dependent variable:</i> |                       |                       |                       |                       |
|----------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Commuting flow (log)       |                       |                       |                       |                       |
|                            | (1)                   | (2)                   | (3)                   | (4)                   |
| Time $t_{ic}$              | -0.064***<br>(0.0002) | -0.069***<br>(0.0003) | -0.057***<br>(0.0004) | -0.070***<br>(0.0004) |
| Fixed effects              | Yes                   | Yes                   | Yes                   | Yes                   |
| > 10 commuter              | -                     | Yes                   | Yes                   | Yes                   |
| Group selection            | All workers           | All workers           | Only high income      | Only low income       |
| Observations               | 70,103                | 37,168                | 19,505                | 21,082                |
| R <sup>2</sup>             | 0.931                 | 0.978                 | 0.979                 | 0.975                 |

Fixed effects include municipalities of origin and municipalities of destination. Method is Ordinary Least Square. *Note:* Standard errors in parenthesis. \*p<0.1; \*\*p<0.05; \*\*\*p<0.01

Table 4.F.1 and 4.F.2 in appendix 4.F present the results for the same regressions applied to commuting flows made by public transit (table 4.F.1) and by car and motorcycle (table 4.F.2). Results are similar to those of table 1, but coefficients are lower for public transit (around 0.4 - 0.5), and slightly higher for cars (around 0.6 - 0.7). This suggests that the marginal effect of transport time by car is slightly greater than by public transit. One explanation could be that the monetary cost per supplementary kilometer is higher for private vehicles than for public transit. Therefore, a higher time also implies a higher monetary cost, which is not desirable, particularly if one car-drives. However, given that the coefficients are of the same order of magnitude, we assume as a first order approximation that workers value similarly the time by public transit or by car.

### 4.7.2 Results for the hedonic pricing model

Table 4.H.1 in appendix 4.H presents the results for the estimation of equation (4.12). The model is estimated using a gravity-accessibility to all jobs and a spatial decay parameter of 0.064. In columns (1) and (2), we run the model at the municipal level, with average rent and prices per square meter for the year 2010. Since we use average values per square meter, the model does not include structural property-level variables. In columns (3) and (4), we use property transaction data for the year 2015. In column (3), we restrict the sample to apartments. The plot surface does not intervene. In column (4), we consider houses only and control by the built surface and the plot surface. The dummies for Paris and the inner suburbs control for the distance to the center. We include the

## 4.7. Results

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month of the transaction as a control variable, since real estate prices may be subject to seasonal variations. Amenity controls include the share of dwellings that are social housing in the municipality, natural amenities and potential nuisances (airport, transport infrastructure), as in the population composition regressions. For all columns, we use the value of accessibility to employment and amenities for the same year as housing values data.

We find that accessibility to employment plays a significant positive role in the hedonic pricing model. The price-elasticity of accessibility is significantly lower in the model with average values at the municipal level (0.14 and 0.17) than in the model with property prices (around 0.42). This may be due to different behavior between renters and buyers, but could also be explained by the different specifications of the models (average value VS model with controls for dwelling characteristics). We find values close to those found in the existing literature. Using the same functional form for accessibility, Ahlfeldt (2013) finds 0.4 for London and Osland and Thorsen (2008) find 0.25 for the Rosaland region.

### 4.7.3 Results of regression of income sorting on accessibility.

Using a spatial decay parameter of 0.064, we estimate changes in population composition as a result of changes in accessibility to employment. Table 2 presents the results of the estimation of equation (4.18). Coefficients of the first two lines capture the effects of changes in accessibility due to improvement in the public transit network, between  $t - 1$  and  $t$ , and between  $t - 2$  and  $t - 1$  (lagged change in accessibility). In column (1), we restrict the sample to municipalities with a population above 1,000 workers and in columns (2)-(4), above 5,000 workers. Many municipalities in the Paris Region are rural and have a small population. For small populations, the equation (4.4) does not hold, as it only considers the expected share of residents of group  $g$ . It is therefore not surprising that, in small municipalities, our model has a weak explanatory power.

The simultaneous effects of changes in accessibility to employment due to changes in the transport times do not have a p-value below 0.01. However, the changes in the previous period are correlated, with positive coefficient significant at the 1% level in columns (2), (3), and (4). In columns (2)-(4), the coefficient for the simultaneous change in accessibility is positive but not significant at the 1% level. The weak correlation for the simultaneous change in columns (2)-(4) may be explained by the fact that some transit network extensions come to operations only at the end of the periods considered, and by the inertia of residential locations (see Appendix 4.G).

Comparison between columns (2), (3), and (4) suggests that the effect of accessibility on residential composition is similar when controlling for local amenities and the share of public housing with group- and period-specific coefficients.<sup>23</sup>

Coefficients for the log of initial population enable us to retrieve the time-lag param-

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<sup>23</sup>Although the low quality of public housing controls should be noted, since the information on the number of public housing per municipality in the past is not available.



## 4.7. Results

ter, since we have:  $\lambda(1-\lambda) = \alpha_4$ . The fact that we find negative coefficients for  $\alpha_4$  implies that the system is dynamically stable (Boarnet et al., 2005). From column (3), our preferred specification, we find  $\alpha_2 = \bar{\mu}_1\lambda(1-\lambda) = 1.74 \pm 0.55$  and  $\lambda(1-\lambda) = 0.034 \pm 0.007$ , therefore we have roughly  $\bar{\mu}_1 \approx 55 \pm 20$ . This value is used in section 4.8.

Table 2: Neighborhood composition model results

|                                | <i>Dependent variable:</i>  |                      |                      |                      |
|--------------------------------|---|----------------------|----------------------|----------------------|
|                                | $\Delta_t \log(n_{ig})$ : Evolution of log-pop. of group $g$ in $i$ |                      |                      |                      |
|                                | (1)   | (2)                  | (3)                  | (4)                  |
| Change in accessibility        | 0.174<br>(0.672)  | 0.766<br>(0.504)     | 0.831<br>(0.524)     | 1.007**<br>(0.506)   |
| Lagged change in accessibility | 1.557**<br>(0.718)  | 1.450***<br>(0.534)  | 1.736***<br>(0.550)  | 1.874***<br>(0.530)  |
| Initial accessibility (log)    | 0.233***<br>(0.036)   | 0.278***<br>(0.033)  | 0.272***<br>(0.037)  | 0.358***<br>(0.036)  |
| Initial population (log)       | -0.122***<br>(0.007)  | -0.017***<br>(0.006) | -0.034***<br>(0.007) | -0.100***<br>(0.009) |
| Amenity controls               | Yes   | -                    | Yes                  | Yes                  |
| Public housing controls        | Yes   | -                    | -                    | Yes                  |
| Location-year fixed effects    | Yes   | Yes                  | Yes                  | Yes                  |
| Group-year fixed effects       | Yes   | Yes                  | Yes                  | Yes                  |
| Initial population > X hab     | 1,000   | 5,000                | 5,000                | 5,000                |
| Observations                   | 8,487   | 4,300                | 4,300                | 4,300                |
| R <sup>2</sup>                 | 0.479   | 0.560                | 0.663                | 0.637                |

Change in accessibility is the difference in log-accessibility due to improvements of the transit network. Amenity controls include share of vacant housing, share of secondary or occasional housing, dummies for distance from the center and distance to the closest airport, land use variables, elevation, and slope, with group-period specific coefficients. Public housing controls include the share of public housing in 2015 with group-period specific coefficients. Method is Ordinary Least Square. *Note:* Standard errors in parenthesis. \*p<0.1; \*\*p<0.05; \*\*\*p<0.01

We perform two main robustness tests in Appendix 4.G. First, we run one-period models with respectively anticipated, simultaneous, and lagged effects of change in accessibility to employment on residential composition. We find non significant anticipated

## 4.8. Anticipating the impacts of the GPE

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effects, suggesting that the changes in accessibility are not linked with past changes in residential composition. The simultaneous effects are also not significant: one reason may be that some new transport infrastructures only opened at the end of the considered periods. On the contrary, we find positive and significant lagged effects for the period following the change in accessibility. The effect disappears after one period. Overall, these sequences of effects gives credit to the underlying causal assumption of our model.

As a second test, we perform the same regressions as in table 2 albeit considering that transport time is simply the transport time by public transit, not the minimum between time by public transit and private car. We present results for the same regressions with this measure of accessibility to employment in appendix 4.G. Results appear qualitatively similar. This suggests that our model is robust to different specifications of accessibility.

## 4.8 Anticipating the impacts of the GPE

In this section, we use the model to anticipate the effect of the GPE on the relative locations of workers given their occupational category. The GPE is a rail-transit project currently under construction in the Paris metropolitan area. It consists of 4 new lines, that are mainly circular and serving the inner suburbs of the metropolitan area, and an extension of an existing radial line (line 14). In total, 200km of new lines are projected, which represents the same length as the total existing “Metro” system in Paris. The cost of the project is estimated at around 40 billion 2012 €(Cour des comptes, 2017). The project is represented on the map of figure 3. Given the scale of the project, one may expect significant impacts on the development of the urban area. Public transit is the dominant mode of transportation in the Paris region, as 54% of commuting trips in 2010 were made with walking or public transit as main mode (census). Moreover, public transit is used by workers of all social groups.<sup>24</sup>

As in section 4.4.2, we assume that the transport project does not alter the location of jobs, the wages for each group  $g$ , the local value of amenities, nor the supply of floorspace at each location. We focus on two effects: (i) the effects on rents and (ii) the effect on the sorting of workers based on their occupational category. We simulate the changes in the composition of neighborhoods as being driven by the changes in accessibility to group-specific jobs. The map of figure 3 presents the projected route of the GPE, as well as the number of jobs and the composition in terms of share of jobs that are occupied by high-income occupational categories. The map shows that the GPE will travel through municipalities with a variety of job compositions.

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<sup>24</sup>For instance, 52% of managers and intellectual professions workers use public transit or walking as main mode, compared to 48% for intermediate occupations, 57% for sales, services, and clerical workers, and 45% for blue-collar workers (source: census 2010).

## 4.8. Anticipating the impacts of the GPE

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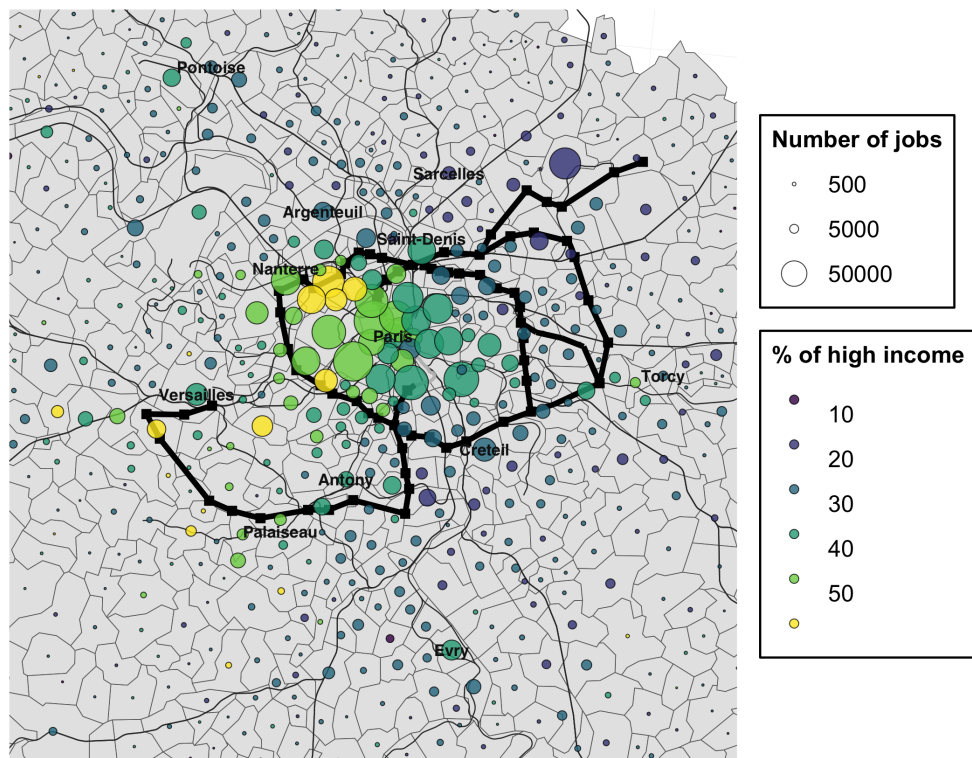


Figure 3: Employment composition and location of the GPE.

Note: Circle sizes represent the total number of jobs per municipality occupied by employed workers aged 25-54, in 2010. The circle colors represent the share of these jobs that are occupied by high-income occupational categories (see appendix 4.B). The solid black line represents the projected route of the GPE. Source: INSEE, census 2010.

## 4.8. Anticipating the impacts of the GPE

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### 4.8.1 Effect of the GPE on rents

The equation that predicts the impact of the GPE is equation (4.8). We provide forecasts of the impact of the GPE on rents in appendix 4.I. One key assumption is whether the city is “closed” or “open” (see section 4.4.2). To which extent should the impacts of public transit be studied under the closed or open city assumption depends on whether public transit is a driver of metropolitan growth. This remains an open question. Duranton and Turner (2012) find a significant but small effect of bus transit on the growth of US metropolitan areas. Given the extent of the GPE project, its expected impact on the growth of Paris metropolitan area may be important. In practice, open and close cities arguably represent two extreme cases, with the reality being in between. In the closed city case, the GPE can have a negative effect on rents in municipalities even though they are served by the new project. We show this on figure 4.I.1 of appendix 4.I, which presents the simulated results of the GPE on rents in municipalities located at less than 200m from a projected station of the GPE. With an price-elasticity of accessibility to employment of 0.4, the effect of the GPE on local rents range between  $-2\%$  and  $13\%$ .

The main models developed to anticipate transit-induced changes in rents make the assumption of a representative agent (Ahlfeldt, 2013; Vigié and Hallegatte, 2014). One question is whether accounting for heterogeneous groups changes significantly the predicted changes in rents. We simulate the predicted effects on rents in the case with only one group of workers ( $G = 1$ ), and considering the accessibility to all jobs. On figure 4.I.1 of appendix 4.I, we represent the distribution of differences between the predicted changes in rents (in %) when accounting, or not, for heterogeneous occupational workers. We find similar results, suggesting that models with a representative agent are a good first-order approximation.

### 4.8.2 Effect of the GPE on neighborhood compositions

Using equation (4.8), we can simulate the change in equilibrium population between the situation with and without the GPE. In order to account for uncertainty, we simulate the effects of the GPE for a range of values for the elasticities  $\beta/\gamma$  and  $\mu$ , as well as for the spatial decay parameter  $\tau$ , in both the closed and open city cases. We derive the range of values for the parameters from the results of section 4.7. From section 4.7.1, we consider that the parameter  $\tau$  can take the value of 0.05, 0.06, or 0.07. For the ratio  $\gamma/\beta$ , given the results of section 4.7.2, we assume that it takes the values of 0.2 or 0.4. From section 4.7.3, we assume that  $\mu_1 = (\mu + 1)\gamma/\beta$  takes the value of 35, 55, or 75. We simulate the effect of the GPE, all else equal, for the set of  $3 \times 2 \times 3$  possibilities for the different values of the parameters, in both the closed and open city cases (36 simulations). Figure 4 presents the results of our simulations on the share of high-income workers in each municipality, based on the 36 simulations. We consider a significant increase in the share of high-income workers as an increase greater than 1% (and similarly for a decrease). In

## 4.9. Discussion: the distributional effects of public transit policy

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municipalities for which the effect is between  $-1\%$  and  $+1\%$ , we consider that the GPE has “no effect”.

The effect of the GPE on income sorting are heterogeneous along the lines. In locations that are close to high-income jobs, notably the locations close to La Defense (in the western part of the inner suburbs) and the center of Paris, the new project decreases the difference in accessibility between high- and low-income workers, therefore leading to a decrease in the share of high-income workers. On the contrary, in locations that were initially not accessible for high-income workers, such as on southern part of the future line 14, or on the northern part, we simulate an increase in high-income residents. Overall, the distribution of municipalities served by the GPE is skewed towards an increase in high-income residents (see figure 4, graph below). We anticipate the GPE to have a positive effect on gentrification in a majority of the municipalities served.

### 4.8.3 Aggregate effect of the GPE

Eventually, we discuss the aggregate effect of the GPE on utility, within the framework presented above. Given the assumptions made, gains in accessibility always result in higher utility levels. However, whether the gains in utility are higher for high- or low-income workers is unclear. Within the considered framework, the changes in utility in the closed city case is a measure of the aggregate increase in accessibility for workers of a given group. In table 3, we present as an example the difference in utility increase between occupational category 3 (managers, intellectual occupations) and lower-income occupational categories (OC 4-6), for scenarios in which only part of the lines of GPE are implemented. There are important differences depending on the line: line 16 and 17 yield much higher gains in utility for OC4-6, because they serve low-skilled job area in the North-East of Paris. On the contrary, workers from OC3 benefit more from line 18. The last line presents the overall effect when all lines of the GPE are built. In this case, the increase in utility is slightly higher for low-income occupational category workers.

The framework used here therefore enables us to determine how aggregate accessibility increases for each category. Table 3 shows that the results depend on the line. Within our framework, new public transit is therefore not *a priori* a “pro-poor” or “pro-rich” policy. However, our framework omits some elements of the analysis that could be included in a general welfare analysis of public transit. In the next section, we discuss the general distributional effects of public transit.

## 4.9 Discussion: the distributional effects of public transit policy

The model developed in this work highlights a simple mechanism that drives transit-induced changes in the sorting of inhabitants. One of the key characteristics of this model is that the *ex ante* effects of new public transit infrastructure are undetermined

#### 4.9. Discussion: the distributional effects of public transit policy

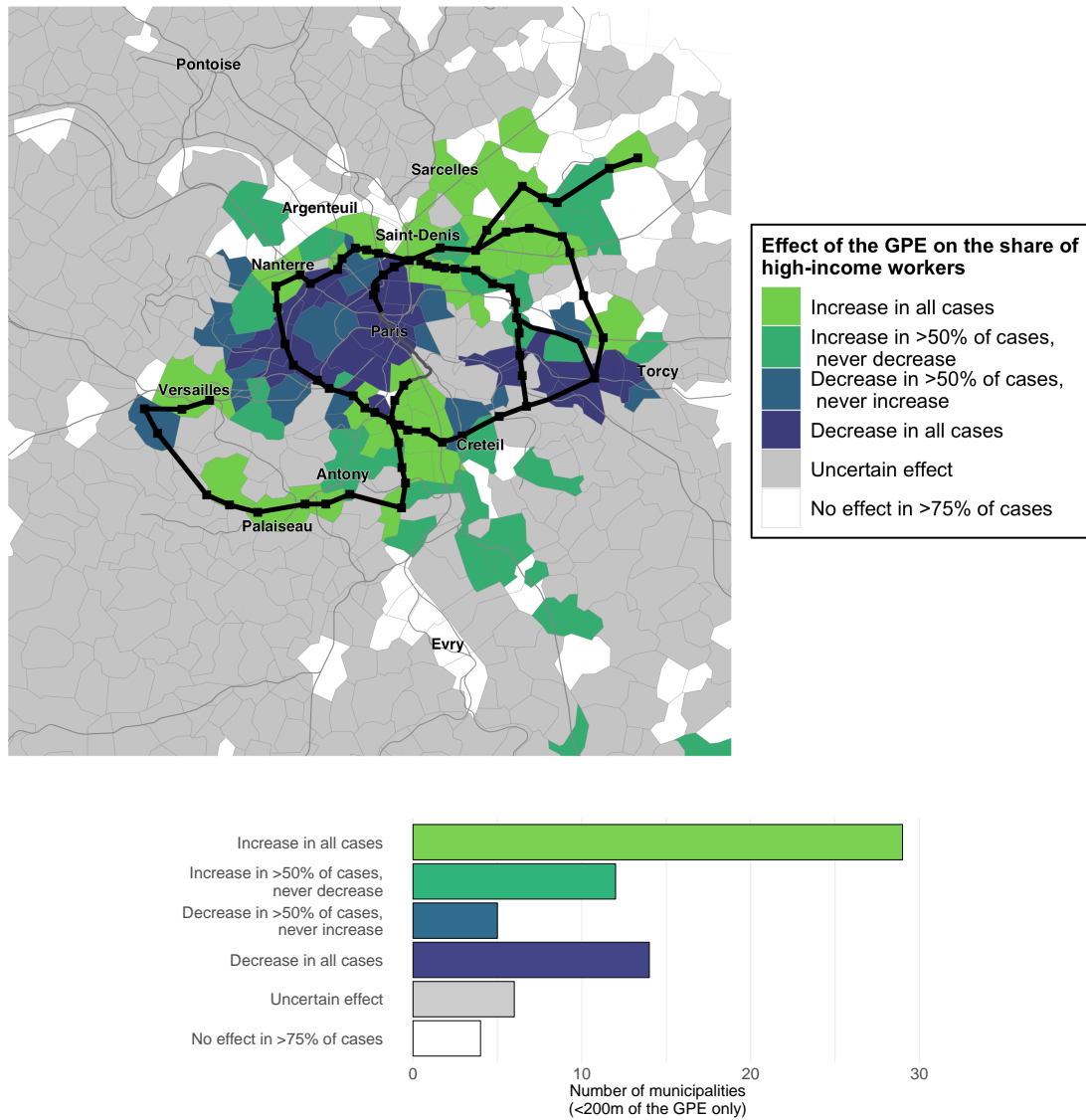


Figure 4: Simulated effect of the GPE on the share of high-income workers.

Indicator built on the results of 18 simulations. “Uncertain effect” captures all the municipalities that are not included in the 5 other categories. The distribution of municipalities (below) concerns only municipalities located at less than 200m from a GPE stations. High income occupational categories include entrepreneurs, executive directors, managers, and intellectual professions.

#### 4.9. Discussion: the distributional effects of public transit policy

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Table 3: Differences in gains in utility between occupational categories in several scenarios

| Scenario      | Difference in gains in utility<br>compared to OC3 (%) |        |       |        |
|---------------|---|--------|-------|--------|
|               | OC3   | OC4    | OC5   | OC6    |
| Lines 11-14   | 0   | + 5.7  | + 8.1 | + 3.3  |
| Line 15       | 0   | -0.1   | -5.5  | + 1.9  |
| Line 16       | 0   | + 58.3 | + 69  | + 64.6 |
| Line 17       | 0   | + 47.2 | + 52  | + 83.6 |
| Line 18       | 0   | -10.3  | -17.3 | -19.9  |
| All lines GPE | 0   | + 3.3  | + 0.9 | + 9.1  |

Gains in utility in the closed city case with  $\gamma/\beta = 0.4$ ,  $\mu_1 = 55$ . “OC” stands for for Occupational Categories, see appendix 4.B for their definitions. OC 3 (managers, intellectual professions is used as reference). “Line 11-14” corresponds to the extension of these lines. Other lines are created.

and depend on the geography of the transit network. Such a mechanism is in line with previous empirical literature that finds heterogeneous effects of public transit on gentrification. While planning extensions of a public transit network, there may be trade-offs or synergies between cost-efficiency and social benefits, depending on the objectives pursued by the local transport planner. Overall, our results suggest that the choice of the locations of lines and stations has an influence on the distributional impacts.

However, we have not accounted for all potential drivers of income sorting related to transit. In particular, we assumed in this work that individuals choose their transport mode only by minimizing transport times and that the valuation of time is proportional to income. Under such assumptions, the differences in accessibility to employment are only caused by differences in the locations of jobs. However, existing evidence suggests that the value of time varies with income (Börjesson et al., 2012). Moreover, the monetary costs of transport are not negligible (Van Ommeren and Dargay, 2006). Following LeRoy and Sonstelie (1983) and Glaeser et al. (2008), one could argue that the differential in monetary cost between modes drive the sorting of inhabitants based on income. There is also evidence that travel behaviors are heterogeneous between income groups. In particular, urban transport demand appears to be an increasing function of income (Golob, 1989), potentially driven by leisure activities. In this work, we chose a simple functional form for accessibility. Our framework could be adapted to incorporate more complex specification for accessibility, that would include (i) the monetary cost of transport, and

## 4.9. Discussion: the distributional effects of public transit policy

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(ii) more complex travel behaviors. This is left for future research.<sup>25</sup>

We also provided a simple representation of the housing market. In practice, the distributional impact of public transit improvement highly depends on who owns the land or the dwellings, and therefore who benefits from local changes in housing value (see e.g. Borck and Wrede, 2005, who make this argument in the case of transport subsidies). In the Paris region, the population is split between renters and owner-occupants (in 2016, 47.2% of residents were owner-occupants, according to the INSEE), suggesting there can be strong distributional impacts. Moreover, welfare effects are particularly sensitive to the specification of the valuation of housing consumption. We considered here that welfare is log-linear in housing consumption (Cobb-Douglas function). If we had considered a more realistic functional form, such as a Stone-Geary function as in chapter 3, the welfare of low-income residents would have been more sensitive to the “decongestion” of urban land. However, by considering a more complex functional form, we lose the explicit relationship between accessibility and neighborhood composition, given by equation (4.13).

General equilibrium effects include impacts on the productive sector, that are out of the scope of this chapter. New public transit may generate heterogeneous agglomeration externalities depending on the industry considered. Moreover, public transit project such as the GPE may also alter the location of employment opportunities. How such effects alter the distributional impact of public transit is *ex ante* undetermined. We chose here to decompose the problem, and focus for the first part on the location choices of residents. This may be justified on the facts that employment distribution remained relatively stable in the past and that the most important changes were due to large-scale planning projects. Extensions of this framework with endogenous employment location is left for future research.<sup>26</sup>

Eventually, a complete discussion on the distributional benefits of public transit should include the broader externalities. How congestion relief, air pollution and noise reductions are distributed in the population remains an open question. For instance, there is evidence that lower-income households tend to live in areas with poorer air quality, and to suffer more health consequences from air pollution (Finkelstein et al., 2003). Therefore, they may benefit more from a reduction in air pollution induced by a modal shift towards public transit. Being able to anticipate, for a given transport project,

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<sup>25</sup>Note that introducing these elements to the measure of accessibility could lead to contradictory conclusions regarding the distributional impact of public transit. On the one hand, considering the monetary cost of public transit (assuming that it is lower than for car), one could argue that public transit policy, because they permit modal shift towards a cheaper mode, are more beneficial for low-income commuters. On the other hand, if travel time savings are valued more for high-income commuters, either because their valuation of time is greater, or because they commute more frequently, such a conclusion would be reversed.

<sup>26</sup>For a general equilibrium model with both location choices from industries and inhabitants, with a decomposition of the welfare effects of public transit, see Tsivanidis (2018). The drawback of such general equilibrium model is a greater complexity.



## 4.10. Conclusion

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the distribution of externality effects appears to be still beyond current state-of-the-art research and policy evaluation.

## 4.10 Conclusion

As reviewed in section 4.2, existing literature find contradictory or mixed results for the effects of the extensions of public transit networks on the social composition of neighborhoods, making it difficult to conclude on a systematic effect. Existing empirical assessments compare locations “treated” by public transit infrastructure to locations that are not. Here, we use a different approach, a group-specific measure for accessibility, and show that it enables to understand why the impact of public transit on income sorting may depend on the location of the neighborhoods and on the geography of the transit network.

We provide a general framework to anticipate potential transit-induced changes in the composition of neighborhoods, based on standard assumptions from the urban economic literature applied to multiple types of workers. The model is simple but enables to disentangle the local and equilibrium effects on the housing market. It provides a tractable equation between changes in accessibility and changes in the composition of neighborhoods. We empirically test our model on the Paris region. Using unique estimations of transport times by public transit between 1968 and 2010 derived from a transport model, we show that historical openings of public transit lines can be linked to changes in the composition of neighborhoods in a way that is consistent with the model outcomes. Moreover, the effect appears robust to several alternative specifications.

This framework can be used to prospectively simulate changes induced by new transit infrastructures. We illustrate this by assessing potential changes due to the GPE project. We anticipate the GPE to cause an increase in the share of high-income residents in a majority of the municipalities served. However, the effects are heterogeneous across the lines and the locations. We also discuss the distribution of welfare gains induced by the project. We simulate heterogeneous effects on utility depending on the line of the project considered. Overall, we find higher gains in utility for low-income occupational categories, suggesting that *even if the project induces gentrification, it may have an overall progressive effect*. We also carry out an in-depth sensitivity analysis across a wide range of values for the model parameters, and show that these results are robust.

The simplicity of the model makes it easily readable and adaptable to other transport projects in other cities. In addition, it represents a simple analytical framework that could be adapted in the future to incorporate more advanced representations of accessibility and of the housing market, as discussed in section 4.9.

# Appendices

## 4.A Calculation for part 4.4.2

The ratio of the number of workers of group  $g$  living in  $i$  is:

$$\frac{n_{ig}^P}{n_{ig}} = \left( \frac{a_{ig}^P}{a_{ig}} \right)^{\frac{\gamma}{\beta}(1+\mu)} \left( \frac{u_g^P}{u_g} \right)^{-\frac{(1+\mu)}{\beta}} \left( \frac{\sum_h (\psi_{ih}^P)^\mu}{\sum_h (\psi_{ih})^\mu} \right)^{-1} \quad (4.20)$$

In equation (4.7), we write  $\psi_{ih}^P$  as a function of  $\psi_{ih}$  using equation (4.6):

$$\psi_{ih}^P = \left( \frac{a_{ih}^P}{a_{ih}} \right)^{\frac{\gamma}{\beta}} \left( \frac{u_h^P}{u_h} \right)^{-\frac{1}{\beta}} \psi_{ih} \quad (4.21)$$

Moreover, using equation (4.5) applied to two groups of workers  $h$  and  $k$ , we have:

$$\frac{\psi_{ih}}{\psi_{ik}} = \left( \frac{n_{ih}w_h}{n_{ik}w_k} \right)^{\frac{1}{1+\mu}} \quad (4.22)$$

Therefore, we can write:

$$\sum_h (\psi_{ih}^P)^\mu = \frac{\psi_{ik}}{(n_{ik}w_k)^{\frac{\mu}{1+\mu}}} \sum_h \left( \frac{a_{ih}^P}{a_{ih}} \right)^{\frac{\gamma\mu}{\beta}} \left( \frac{u_h^P}{u_h} \right)^{-\frac{\mu}{\beta}} (n_{ih}w_h)^{\frac{\mu}{1+\mu}} \quad (4.23)$$

where  $k$  is any income group. Similarly, we have:

$$\sum_h (\psi_{ih})^\mu = \frac{\psi_{ik}}{(n_{ik}w_k)^{\frac{\mu}{1+\mu}}} \sum_h (n_{ih}w_h)^{\frac{\mu}{1+\mu}} \quad (4.24)$$

Log-linearizing equation (4.7) and plugging expressions from equations (4.23) and (4.24), we finally obtain:

$$\log \frac{n_{ig}^P}{n_{ig}} = \frac{\gamma(1+\mu)}{\beta} \log \left( \frac{a_{ig}^P}{a_{ig}} \right) - \frac{(1+\mu)}{\beta} \log \left( \frac{u_g^P}{u_g} \right) - \log \left( \frac{\sum_h \left( \frac{a_{ih}^P}{a_{ih}} \right)^{\frac{\gamma\mu}{\beta}} \left( \frac{u_h^P}{u_h} \right)^{-\frac{\mu}{\beta}} (n_{ih}w_h)^{\frac{\mu}{1+\mu}}}{\sum_h (n_{ih}w_h)^{\frac{\mu}{1+\mu}}} \right) \quad (4.25)$$

## 4.B. Occupational categories

### 4.B Occupational categories

We present on table 4.B.1 the definitions of occupational categories and their population in 2010. On the fourth column, we estimated the average wage based on individual survey (DADS), in 2010. These values are used for the simulations in section 4.8. Finally, the last column of the table presents the category high-, middle- and low-income that are used in this chapter (in particular in section 4.3).

Table 4.B.1: Definition of occupational categories

| Occupational category | Description                          | Total workers | Average wage | Income group |
|-----------------------|--------------------------------------|---------------|--------------|--------------|
| 1                     | Farmers                              | 48            | -            | -            |
| 2                     | Executive directors, entrepreneurs   | 47,988        | 39,754       | High-        |
| 3                     | Managers, intellectual occupations   | 1,368,528     | 38,607       | High-        |
| 4                     | Intermediate occupations             | 1,121,760     | 24,124       | Middle-      |
| 5                     | Sales, services and clerical workers | 1,998,672     | 15,583       | Low-         |
| 6                     | Blue-collar workers                  | 902,328       | 16,402       | Low-         |

Note: Total workers corresponds to the number of employed workers working and living in the Paris region in 2010. Average wage is the average annual net wage for an employed worker, in 2010 euros. Source: INSEE, *Déclaration Annuelle de Données Sociales* (DADS), 2010.



Figure 4.B.1: Distribution of net annual wage in 2010 for employed workers in the Paris Region, as a function of occupational category.

Note: group 1 (“Farmers”) were removed from the sample. Source: INSEE, *Déclaration Annuelle de Données Sociales* (DADS), 2010.

#### 4.C. Evolution of employment distribution across municipalities in the Paris region, 1968-2010

### 4.C Evolution of employment distribution across municipalities in the Paris region, 1968-2010

Figure 4.C.1 shows the distribution of jobs for employed workers aged 25-54 across municipalities of the Paris region, by income group, in 1968 (x-axis) and 2010 (y-axis). The figure shows the stability over time in the spatial distribution of group-specific employment, as the dispersion from the  $y = x$  line is limited. Moreover, the municipalities that are the most distant from the line are specific municipalities, where specific planning interventions resulted in an “above average” job creation. These interventions include the construction of a new airport (Roissy-en-France, Roissy-en-Brie), the logistic center in Rungis, the “Villes Nouvelles” planning program (Evry, Elancourt, Guyancourt, Cergy, Montigny-Le-Bretonneux, Lieusaint, Savigny-le-Temple, Noisiel, Courcouronnes, Lognes), and the creation of the business district of La Défense (Puteaux, Courbevoie).<sup>27</sup>

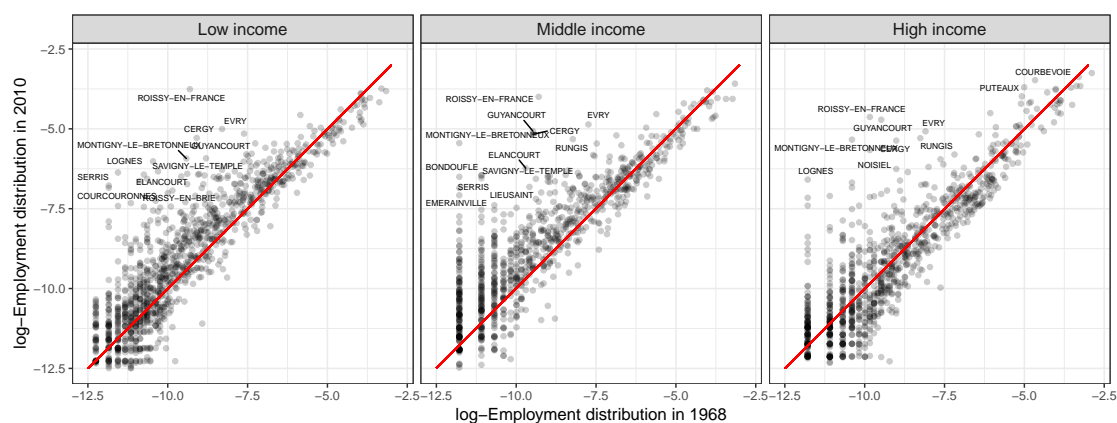


Figure 4.C.1: Employment distribution across municipalities in 2010 (y-axis) and 1968 (x-axis), by income group.

Note: The data used is the number of employed workers aged between 25 and 54 by municipality of employment, in the Paris region (Ile-de-France). The employment distributions are calculated so that the sum across all municipalities for a group and a year is 1. Source: INSEE, Census 1968-2010 (normalized for comparison).

<sup>27</sup>More anecdotally, the municipality of Serris is where Disneyland Paris was built in 1992.

## 4.D. Evolution of transport times between 1968 and 2010

### 4.D Evolution of transport times between 1968 and 2010

Using the MODUS model, we compute the average transport time between location in the Census years between 1968 and 2010. The MODUS model is encoded with the transit network as of 2010. We retrieve a dataset of extensions of the public transit network of the Paris metropolitan area using the Wikipedia pages for the subway, suburban trains and tram lines. The information gathered is summarized in table 4.D.1. We then remove from the transit network in 2010 the corresponding segment of routes, the missions, the stations or the entire lines, in order to approximate the transit network that existed in previous years. We then use a shortest path algorithm to compute the minimum transport time by public transit between pairs of municipalities. An example of output is presented on figure 4.D.1.

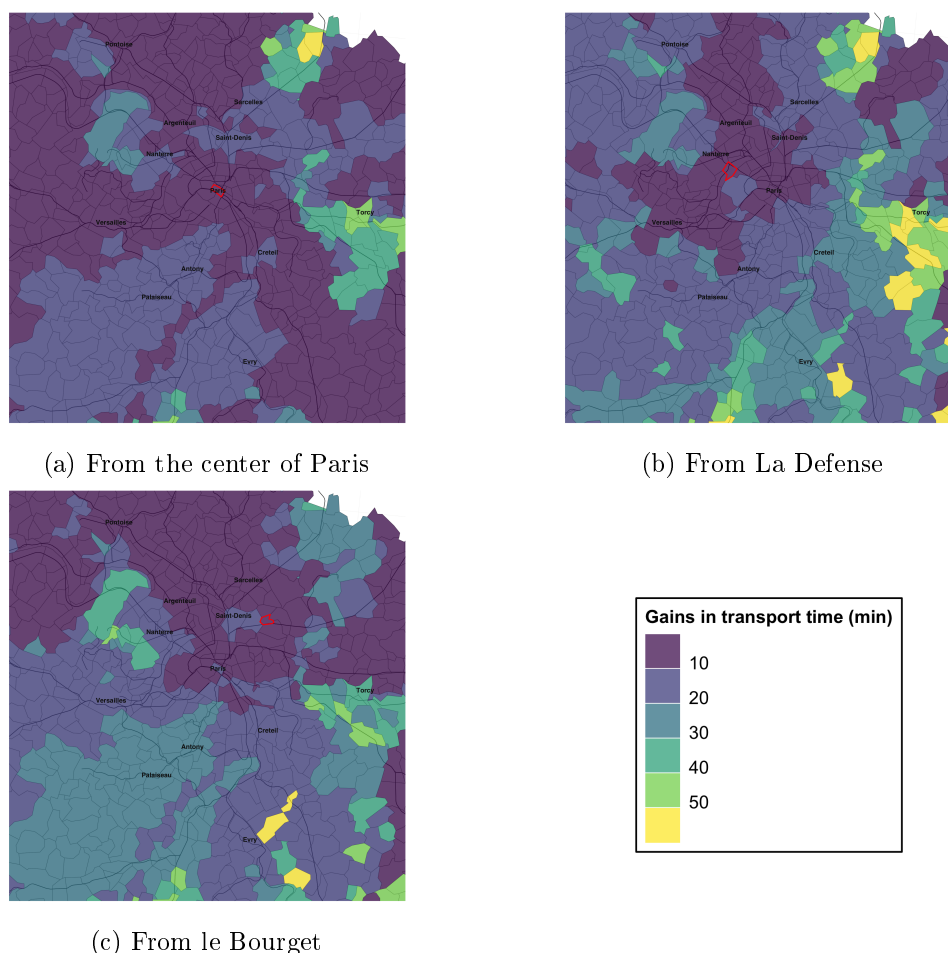


Figure 4.D.1: Simulated changes in commuting times by public transit from different municipalities of origin between 1968 and 2010.

Note: Municipalities of origin are highlighted in red on the maps. Evolution of transport times between 1968 and 2010 computed using the MODUS model.

#### 4.D. Evolution of transport times between 1968 and 2010

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Table 4.D.1: Main extensions of the rail public transit between 1968 and 2010

| Year        | Intervention on the network  | Type of rail transit |
|-------------|------------------------------|----------------------|
| 1999 – 2010 | Extension M13                | subway               |
|             | Extension RER A              | suburban train       |
|             | Extension M14                | subway               |
|             | Extension RER C              | suburban train       |
|             | Extension Tram T1            | tram                 |
|             | Extension Tram T2            | tram                 |
|             | Creation Tram T3A            | tram                 |
|             | Creation Tram T4             | tram                 |
|             | Creation RER E               | suburban train       |
| 1990 – 1999 | Extension M1                 | subway               |
|             | Extension M13                | subway               |
|             | Extension RERA               | suburban train       |
|             | Extension RERB               | suburban train       |
|             | Extension RERC               | suburban train       |
|             | Creation RER D               | suburban train       |
|             | Creation Tram T1             | tram                 |
|             | Creation Tram T2             | tram                 |
|             | Creation M14                 | subway               |
|             | Creation line U              | suburban train       |
| 1982 – 1990 | Extension M5                 | subway               |
|             | Extension M7                 | subway               |
|             | Extension RER A              | suburban train       |
|             | Extension RER B              | suburban train       |
|             | Extension RER C              | suburban train       |
| 1975 – 1982 | Extension M7                 | subway               |
|             | Extension M10                | subway               |
|             | Extension M13                | subway               |
|             | Creation RER A (second part) | suburban train       |
|             | Creation RER B               | suburban train       |
|             | Creation RER C               | suburban train       |
| 1968 – 1975 | Creation RER A (first part)  | suburban train       |
|             | Extension M3                 | subway               |
|             | Extension M8                 | subway               |
|             | Extension M13                | subway               |

### 4.E Amenity controls: variables and data sources

We use the Corine Land Cover to retrieve information on land uses from 1990 to 2010.<sup>28</sup> We compute the share of the surface of each municipalities occupied by specific land uses: water (e.g. lakes, rivers), forests, green urban area, dump sites and transport infrastructure (excluding airports). Because Corine Land Cover data is not available before 1990, we assume that the values are constant between 1968 and 1990. Using an elevation dataset<sup>29</sup>, we calculate the average elevation and slope per municipality. We also compute the distance from the closest large airport in service. The Paris region has three large airport, among which the Roissy Charles-de-Gaulle airport, which was opened in 1974.

We also include controls for the type of housing and its occupation status. In particular, given the scale of social housing in the Paris Region, it should be an important control variable for the regressions on social group sorting.<sup>30</sup> Because of limited data availability, we use the share of dwellings that are public housing per municipality in 2015, derived from the national census. We assume that this share was constant between 1968 and 2015. This serves as a first-order approximation given data availability. We also include the share of dwellings that are vacant and the share that are secondary or occasional, between 1968 and 2010, from Census data. We assume that vacant housing represents a disamenity while secondary housing reflects attractiveness of the location for occasional inhabitants.

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<sup>28</sup>The Corine Land Cover is provided by Copernicus, available at: <https://land.copernicus.eu/pan-european/corine-land-cover>

<sup>29</sup>The Copernicus Digital Elevation Model, available at: <https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1>

<sup>30</sup>In Paris, about a fifth of housing is social housing. There exists three main types of social housing in France. Availability of historical data about social housing and its occupation is limited. In particular, social housing may not be occupied by the lowest income households. See Lévy-Vroelant et al. (2014) for a review of the context and functioning of social housing in France.

#### 4.F. Supplementary results for gravity regression

#### 4.F Supplementary results for gravity regression

Table 4.F.1: Results from the gravity model: commuting by public transit

| <i>Dependent variable:</i>              |                       |                       |                       |                       |
|---|-----------------------|-----------------------|-----------------------|-----------------------|
| Commuting flows by public transit (log) |                       |                       |                       |                       |
|   | (1)                   | (2)                   | (3)                   | (4)                   |
| Time by public transit                  | -0.043***<br>(0.0002) | -0.049***<br>(0.0003) | -0.042***<br>(0.0004) | -0.051***<br>(0.0004) |
| Fixed effects                           | Yes                   | Yes                   | Yes                   | Yes                   |
| > 10 commuters                          | -                     | Yes                   | Yes                   | Yes                   |
| Group selection                         | All workers           | All workers           | High income           | Low income            |
| Observations                            | 45,857                | 21,438                | 9,921                 | 13,258                |
| R <sup>2</sup>                          | 0.929                 | 0.981                 | 0.981                 | 0.978                 |

Sample was restricted to commute made by public transit and walking. Fixed effects include municipalities of origin and municipalities of destination. Method is Ordinary Least Square. *Note:* Standard errors in parenthesis. \*p<0.1; \*\*p<0.05; \*\*\*p<0.01

Table 4.F.2: Results from the gravity model: commuting by car

| <i>Dependent variable:</i>   |                       |                       |                      |                      |
|------------------------------|-----------------------|-----------------------|----------------------|----------------------|
| Commuting flows by car (log) |                       |                       |                      |                      |
|                              | (1)                   | (2)                   | (3)                  | (4)                  |
| Time by car                  | -0.065***<br>(0.0002) | -0.073***<br>(0.0004) | -0.060***<br>(0.001) | -0.071***<br>(0.001) |
| Fixed effects                | Yes                   | Yes                   | Yes                  | Yes                  |
| > 10 commuter                | -                     | Yes                   | Yes                  | Yes                  |
| Group selection              | All workers           | All workers           | High income          | Low income           |
| Observations                 | 60,399                | 27,570                | 13,340               | 12,574               |
| R <sup>2</sup>               | 0.914                 | 0.976                 | 0.977                | 0.973                |

Sample was restricted to commute made by private car and motorcycle. Fixed effects include municipalities of origin and municipalities of destination. Method is Ordinary Least Square. *Note:* Standard errors in parenthesis. \*p<0.1; \*\*p<0.05; \*\*\*p<0.01



## 4.G Robustness checks for main regression

### 4.G.1 Anticipated, simultaneous, and lagged effects of change in accessibility on residential composition

In this section, we decompose the sequencing of the effect of change in accessibility to employment on residential composition. We adapt the main model of section 4.5.3 in order to highlight anticipated, simultaneous, and lagged effect of changes in accessibility to employment on changes in local population of each group. More precisely, we run the following model:

$$\Delta_{\tau} \log(\bar{n}_{ig}) = \alpha_1 [\Delta_t \log(a_{ig})]_{\text{trans}} + \alpha_3 \log(a_{ig,t_{init}}) - \alpha_4 \log(\bar{n}_{ig,t_{init}}) + \sum_k \gamma_{gkt} \zeta_{ik,\tau} + \nu_{it} + \theta_{gt} + \tilde{\varepsilon}_{igt}$$

where  $t$  is the considered period of changes in accessibility,  $t_{init}$  is the considered initial state, and  $\tau$  can be either anterior, simultaneous, or posterior to  $t$ . We consider two sets of models:

- *three-period* models, where we consider the changes in accessibility during the periods 1975-1982, 1982-1990, 1990-1999, and 1999-2010; where  $\tau$  is either  $t - 1$ ,  $t$ , and  $t + 1$ ; and  $t_{init} = t - 1$
- *five-period* models, where we consider the changes in accessibility during the periods 1982-1990 and 1990-1999; where  $\tau$  is either  $t - 2$ ,  $t - 1$ ,  $t$ ,  $t + 1$ , and  $t + 2$ ; and  $t_{init} = t - 2$

The five-period set of models enables for the observation of two anticipated and two lagged periods. This greater depth comes at the expense of less observations, since the model can only be tested on changes on the transit network that happened between 1982 and 1999.

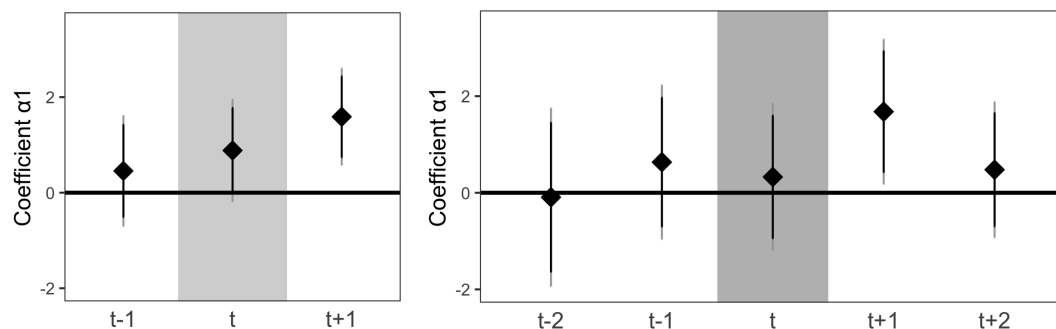


Figure 4.G.1: Estimated coefficients  $\alpha_1$  for 3-period models (left) and 5-period models (right)

Note: Coefficient  $\alpha_1$  represents the effect of change in accessibility of residential composition. Black bars represent 90% confidence interval, grey bars represent 95% confidence interval. Detailed results in table 4.G.1.

## 4.G. Robustness checks for main regression

We present results for the two sets of models in Table 4.G.1 and a visual representation of estimated coefficients  $\alpha_1$  on figure 4.G.1. We find no evidence of an anticipated effect of changes in accessibility on residential composition, as the coefficient  $\alpha_1$  is not significant when  $\tau$  is  $t-1$  or  $t-2$ . This suggests that residents do not make long term anticipations on future line openings. We also find no significant simultaneous effect. This may be explained by the inertia of changes in residential composition, but also by the fact that some new line openings only happen at the end of the period. The coefficient  $\alpha_1$  is only significant at the 5% for the models where  $\tau$  is  $t+1$  (similarly to the findings of section 4.7). Overall, these results give credit the assumption of causality of accessibility to employment on residential composition of neighborhoods upon which we built our model. The fact that the coefficient is not significant for the  $t+2$  model also suggests that the effect of changes in accessibility on residential composition disappears after one period (approx. 9-10 years).

Table 4.G.1: Neighborhood composition regression

| <i>Dependent variable:</i>                |                    |                    |                    |                    |                    |                    |                    |                    |
|---|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| Evolution of log-pop. of group $g$ in $i$ |                    |                    |                    |                    |                    |                    |                    |                    |
|   | Three periods      |                    |                    | Five periods       |                    |                    |                    |                    |
|   | $t-1$              | $t$                | $t+1$              | $t-2$              | $t-1$              | $t$                | $t+1$              | $t+2$              |
| Change in accessibility                   | 0.46<br>(0.59)     | 0.88<br>(0.54)     | 1.59***<br>(0.52)  | -0.09<br>(0.94)    | 0.63<br>(0.81)     | 0.33<br>(0.77)     | 1.68**<br>(0.76)   | 0.48<br>(0.71)     |
| Initial accessibility (log)               | 0.12***<br>(0.04)  | 0.16***<br>(0.04)  | 0.25***<br>(0.04)  | 0.13**<br>(0.06)   | -0.04<br>(0.05)    | 0.21***<br>(0.05)  | 0.36***<br>(0.05)  | 0.13***<br>(0.04)  |
| Initial population (log)                  | -0.11***<br>(0.01) | -0.03***<br>(0.01) | -0.04***<br>(0.01) | -0.13***<br>(0.01) | -0.04***<br>(0.01) | -0.03***<br>(0.01) | -0.05***<br>(0.01) | -0.04***<br>(0.01) |
| Amenity Controls                          |                    |                    |                    | Yes                |                    |                    |                    |                    |
| Location-year fixed effects               |                    |                    |                    | Yes                |                    |                    |                    |                    |
| Group-year fixed effects                  |                    |                    |                    | Yes                |                    |                    |                    |                    |
| Observations                              | 3,720              | 3,720              | 3,720              | 2,310              | 2,310              | 2,310              | 2,310              | 2,310              |
| R <sup>2</sup>                            | 0.59               | 0.57               | 0.65               | 0.58               | 0.59               | 0.63               | 0.68               | 0.62               |

Change in accessibility is the difference in log-accessibility due to improvements of the transit network. Amenity controls include share of vacant housing, share of secondary or occasional housing, dummies for distance from the center and distance to the closest airport, land use variables, elevation, and slope, with group-period specific coefficients. Public housing controls are not included here. Sample was restricted to municipalities with initial population above 2,500. Method is Ordinary Least Square. *Note:* Standard errors in parenthesis. \* $p < 0.1$ ; \*\* $p < 0.05$ ; \*\*\* $p < 0.01$

### 4.G.2 Structural estimation with accessibility by public transit

Table 4.G.2 presents the results for the same analysis as for table 2, but with an indicator for accessibility based only on transport time by public transit. In table 4.G.2,

#### 4.G. Robustness checks for main regression

accessibility is defined as:

$$A_{ig} = \sum_c E_{cg} \exp(-\tau^{PT} t_{ic}^{PT})$$

where  $t_{ic}^{PT}$  is the transport time by public transit. We take  $\tau^{PT} = 0.049$  based on the results from table 4.F.1.

Results are qualitatively very similar than in table 2. In particular, all coefficients in columns (2)-(4) have the same sign. Coefficients for change in accessibility are non-significant when we do not exclude municipalities with a low population (column 1). The model with amenity controls yields a coefficient significant at the 5% level for the lagged change in accessibility and at 1% for the simultaneous change.

Table 4.G.2: Neighborhood composition regression - time by public transit

|                                | <i>Dependent variable:</i>  |                     |                      |                      |
|--------------------------------|---|---------------------|----------------------|----------------------|
|                                | $\Delta_t \log(n_{ig})$ : Evolution of log-pop. of group $g$ in $i$ |                     |                      |                      |
|                                | (1)   | (2)                 | (3)                  | (4)                  |
| Change in accessibility        | -0.075<br>(0.230)   | 0.435*<br>(0.226)   | 0.628***<br>(0.226)  | 0.621***<br>(0.219)  |
| Lagged change in accessibility | 0.306<br>(0.226)  | 0.383*<br>(0.220)   | 0.560**<br>(0.219)   | 0.601***<br>(0.212)  |
| Initial accessibility (log)    | 0.275***<br>(0.044)   | 0.321***<br>(0.046) | 0.371***<br>(0.048)  | 0.452***<br>(0.047)  |
| Initial population (log)       | -0.126***<br>(0.007)  | -0.015**<br>(0.007) | -0.035***<br>(0.007) | -0.098***<br>(0.009) |
| Amenity Controls               | Yes   | -                   | Yes                  | Yes                  |
| Public Housing Controls        | Yes   | -                   | -                    | Yes                  |
| Location-year fixed effects    | Yes   | Yes                 | Yes                  | Yes                  |
| Group-year fixed effects       | Yes   | Yes                 | Yes                  | Yes                  |
| Initial population > X hab     | 1,000   | 5,000               | 5,000                | 5,000                |
| Observations                   | 8,505   | 4,300               | 4,300                | 4,300                |
| R <sup>2</sup>                 | 0.455   | 0.557               | 0.634                | 0.637                |

Change in accessibility is the difference in log-accessibility due to improvements in the transit network. Amenity controls include share of vacant housing, share of secondary or occasional housing, share of public housing (in 2015, assumed to be constant), dummies for distance from the center and distance to the closest airport, land use variables and elevation, with group period specific coefficients. Method is Ordinary Least Square. *Note:* Standard errors in parenthesis. \*p<0.1; \*\*p<0.05; \*\*\*p<0.01

### 4.H Results for the hedonic model

Table 4.H.1 presents the result of the hedonic model discussed in section 4.7. Note that, beyond the parameters for accessibility to jobs, the model yields expected values (or signs) for most of the control variables. In particular, the coefficient for the floor area is lower than 1, which is in line with the common result that price is a concave function of surface. Proximity to airports tend to lower the prices, while proximity to water, to forests or to green urban areas make properties more expensive. Average elevation in the municipality also tend to increase the values, although the region is rather flat. Controls for the distance to the center takes the form of ring dummies (Paris, inner suburbs). Note that the premium for a property located in the municipality of Paris (central area of the urban area) is twice as high for houses than for apartments. This is not surprising as houses are rare in Paris.

#### 4.H. Results for the hedonic model

Table 4.H.1: Hedonic pricing model

| Units of observation           | <i>Dependent variable:</i> |                       |                           |                      |
|--------------------------------|----------------------------|-----------------------|---------------------------|----------------------|
|                                | Rent 2010 (log)            | Price 2010 (log)      | Transac. price 2015 (log) |                      |
|                                | (1)                        | (2)                   | (3)                       | (4)                  |
|                                | Municipalities             |                       | Apartments                | Houses               |
| Built surface (log)            |                            |                       | 0.841***<br>(0.007)       | 0.506***<br>(0.009)  |
| Plot surface (log)             |                            |                       |                           | 0.128***<br>(0.003)  |
| Number of rooms dummies        |                            |                       | yes                       | yes                  |
| Month dummies                  | yes                        | yes                   | yes                       | yes                  |
| Accessibility to jobs (log)    | 0.140***<br>(0.003)        | 0.170***<br>(0.003)   | 0.423***<br>(0.008)       | 0.417***<br>(0.004)  |
| Paris dummy                    | 0.496***<br>(0.019)        | 0.786***<br>(0.021)   | 0.425***<br>(0.010)       | 1.141***<br>(0.041)  |
| Inner suburbs dummy            | 0.128***<br>(0.010)        | 0.189***<br>(0.010)   | 0.174***<br>(0.007)       | 0.184***<br>(0.006)  |
| % social housing               | 0.005<br>(0.024)           | -0.086***<br>(0.026)  | -1.031***<br>(0.019)      | -0.317***<br>(0.022) |
| Elevation                      | 0.0002**<br>(0.0001)       | 0.0005***<br>(0.0001) | 0.001***<br>(0.0001)      | 0.001***<br>(0.0001) |
| Slope                          | 0.504***<br>(0.130)        | 0.833***<br>(0.142)   | -0.597***<br>(0.166)      | 0.883***<br>(0.141)  |
| Airport < 2km                  | -0.037***<br>(0.013)       | -0.123***<br>(0.014)  | -0.250***<br>(0.009)      | -0.201***<br>(0.009) |
| Airport 2 < . < 4km            | 0.025*<br>(0.014)          | -0.076***<br>(0.015)  | -0.153***<br>(0.010)      | -0.135***<br>(0.010) |
| % water                        | 0.011<br>(0.074)           | 0.352***<br>(0.082)   | 1.470***<br>(0.065)       | 1.323***<br>(0.072)  |
| % forest                       | 0.007<br>(0.014)           | -0.011<br>(0.015)     | 0.204***<br>(0.020)       | 0.084***<br>(0.015)  |
| % green urban space            | 0.142***<br>(0.038)        | 0.192***<br>(0.042)   | 0.067***<br>(0.017)       | 0.212***<br>(0.033)  |
| % transp. infra. excl. airport | -0.046<br>(0.048)          | 0.099*<br>(0.051)     | 0.014<br>(0.042)          | -0.183***<br>(0.041) |
| % dump                         | -0.350***<br>(0.113)       | -0.532***<br>(0.126)  | -0.752**<br>(0.364)       | -1.232***<br>(0.183) |
| Constant                       | 3.051***<br>(0.017)        | 8.418***<br>(0.018)   | 9.750***<br>(0.045)       | 10.985***<br>(0.057) |
| Observations                   | 3,586                      | 3,606                 | 93,739                    | 37,542               |
| R <sup>2</sup>                 | 0.618                      | 0.687                 | 0.475                     | 0.463                |

% social housing refers to the share of dwellings that is of social housing. Other variables in %X refer to the share of the municipality area occupied by specific land uses. Method is Ordinary Least Square. *Note:* \*p<0.1; \*\*p<0.05; \*\*\*p<0.01

### 4.I Simulated effects of the GPE on rents

The equation that predicts the impact of the GPE is equation (4.8). This equation can be used in both the "open" city and the "close" city case. In the open city,  $u_g^P = u_g$  for all  $g$ . In the closed city case, we adjust the level of utilities in the equilibrium with the GPE in order to keep the number of workers of each group constant. Therefore, for all  $g$  we derive  $u_g^P/u_g$  by solving  $\sum_i(n_{ig}^P - n_{ig}) = 0$ , using a numerical solver. We assumed for this simulation that  $\gamma/\beta = 0.4$ . We define observed rents as the sum of bid-rents weighted by the population of each group, that is:

$$\bar{R} = \frac{\sum_g n_{ig} \psi_{ig}}{\sum_g n_{ig}} \quad (4.26)$$

Whether we solve in the closed or in the open city case has consequences on the impact of the GPE on rents (Viguié and Hallegatte, 2014). From equation (4.6), increasing accessibility necessarily leads to an increase in bid-rents in the open city case, as  $u_g^P/u_g = 1$ . In the closed city case, utilities are adjusted so that the total population per group is similar with and without the project. Therefore, equilibrium adjustments can offset the local gains in accessibility, if they are low compared to gains in other municipalities. In this case, the GPE can therefore have a negative effect on rents in some municipalities, even though they are served by the new project. Figure 4.I.1 presents the simulated results of the GPE on rents in municipalities located in less than 200m from a GPE station. The upper panel shows the distribution of municipalities within 200m of a station depending on the predicted change in rents. The model predicts an effect on rents between  $-2\%$  and  $+12\%$ . As argued above, there can only be negative evolution of rents in the closed city case (left panel), in municipalities where the increase in accessibility is low.

In order to compare the predictions of the model when we account, or not, for the heterogeneity of workers, we run a simulation the predicted effects on rents in the case with only one group on workers ( $G = 1$ ). In this case, we apply equation (4.8) by considering changes in accessibility to all jobs, the average wage for a worker and the total population (all groups included). On the lower panel of figure 4.I.1, we represent the predicted change in rent in the model with homogeneous workers ( $G = 1$ ) as a function of the predicted change in the model with heterogeneous workers ( $G = 5$ ). The predicted values are very close, suggesting that the predictions in terms of changes in rents do not change significantly if we account or not for workers heterogeneity. This suggests that models with a representative agent are a good first-order approximation.

## 4.I. Simulated effects of the GPE on rents

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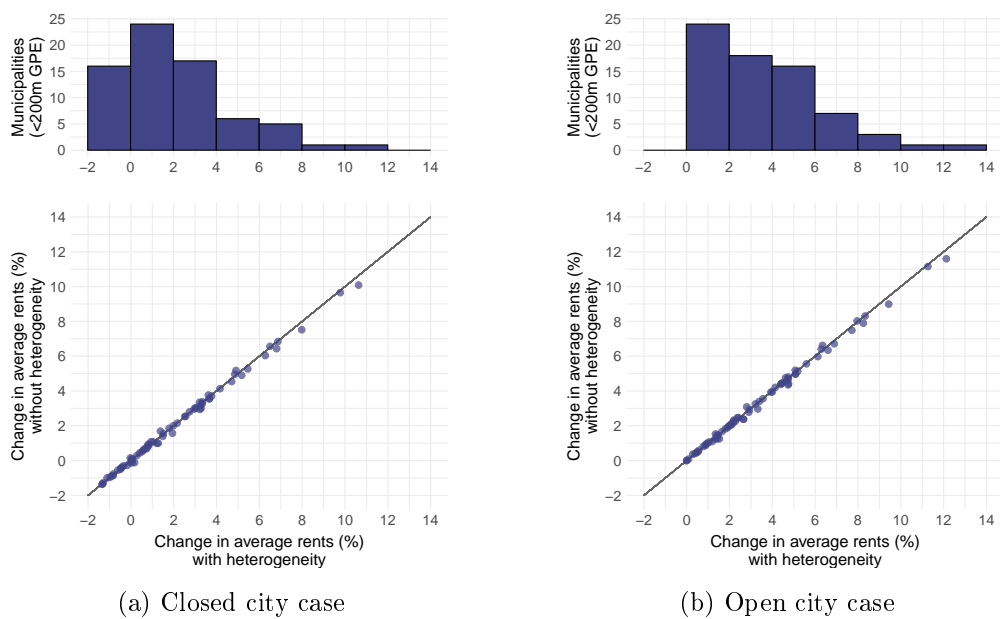


Figure 4.I.1: Simulated effects of GPE on rents, with and without accounting for heterogeneity of commuters.

Note: Top graphs represent the distributions of municipalities as a function of the effect of the GPE on rents. Bottom graphs represent the simulated effect of the GPE on rents without considering heterogeneity in occupational categories, as a function of the simulated effect with the heterogeneity. We considered only the municipalities located at less than 200m from a GPE station.

## Chapter 5

# Assessing urban policies using a simulation model with formal and informal housing: Application to Cape Town, South Africa<sup>1</sup>

*Slums result from a combination of poverty or low incomes with inadequacies in the housing provision system, so that poor people are forced to seek affordable accommodation and land that become increasingly inadequate.*

UN Habitat, *Global Report on Urban Settlements 2003*.

### 5.1 Introduction

In this chapter, we build a simulation model designed for the *ex-ante* assessment of urban policies. As argued in chapter 1, the impacts of urban policies need to be assessed at the scale of a whole city, with the understanding that a city forms a system and that policies can have systemic consequences. For instance, urban planners may try to anticipate how land markets could respond to a major transport infrastructure investment, potentially modifying the spatial organization of a city and its footprint over the long term. Doing so requires an understanding of the market forces that drive city structure, including housing construction decisions, household location and transport mode choice, subject to physical constraints and zoning.

The model from this chapter can be categorized as a Land-Use and Transport In-

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<sup>1</sup>This chapter is adapted from a paper co-authored with Claus Rabe, Harris Selod, and Vincent Vigié. It was published as a World Bank Policy Research working paper under the title “Assessing Urban Policies Using a Simulation Model with Formal and Informal Housing: Application to Cape Town, South Africa”. Errors that may exist in this chapter are my own.



## 5.1. Introduction

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teraction (LUTI) model: it predicts land-use patterns based primarily on transport (or accessibility). Such models have been designed for a few major cities in the world, and various modeling approaches have emerged, including TRANUS (De la Barra, 1989), UrbanSim (Waddell, 2000) and RELU-TRAN (Anas and Liu, 2007) among others (see Acheampong and Silva, 2015, for a full literature review of such models). Although these simulation models have mostly been applied to cities in the United States (US) and Europe, they are increasingly being applied to metropolitan areas elsewhere (see for instance the recent applications of the RELU-TRAN model to Beijing (Anas and Timilsina, 2015) or Beirut (Anas et al., 2017)). In the case of South Africa, a local version of UrbanSim was developed by the Centre for Scientific and Industrial Research (CSIR) for the East Rand area, Durban and Nelson Mandela Bay (see Wray and Cheruiyot, 2015, for a survey of land use modeling in South Africa).<sup>2</sup> Although the development of LUTI models for developing countries is facilitated by improved data availability, it also faces at least three major challenges: first, these models are often complex (involving hundreds of equations) and computationally intensive, which can make them cumbersome to design, difficult to operate, and intractable. Second, because of their complexity and the skills required to operate them, these models may be out of reach and unaffordable to local authorities with limited fiscal resources. Finally, the existing models overlook a key feature of land markets in developing countries: the presence of a *large informal housing sector which coexists and interacts with the formal housing sector* (Durand-Lasserve and Selod, 2009; Napier et al., 2013). This gap precludes analyses of informal housing (which hosts the poor and often a large fraction of the middle class) and of how and the degree to which informal housing affects the whole system. More importantly, because, for many cities, housing informality is far from being a marginal phenomenon, it is possible and even likely that the predictions from models that lack an informal housing sector would not hold if the informal sector were accounted for.

In the face of these challenges, simple urban simulation models that are based in urban economic theory emerge as a less costly alternative to previously developed models (see Arnott, 2012). They are useful for urban planning as they can account for broad patterns of urban development over the long term, while remaining tractable so that users understand the forces at play. The NEDUM model (Viguié et al., 2014) for instance, which was initially developed for the Paris metropolitan area, is an example of such a model.<sup>3</sup> It directly applies a discrete two-dimensional version of the standard urban monocentric model (see Fujita, 1989) on a grid of pixels, accounting for zoning and land availability constraints defined at the pixel level.

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<sup>2</sup>The South African initiatives include a simple cellular-automata model (Dyna-CLUE) that was developed for Johannesburg to investigate land-use conversion processes (Le Roux and Augustijn, 2017). A conceptual framework for an agent-based model of slum evolution was introduced in (Shoko and Smit, 2013).

<sup>3</sup>The acronym NEDUM stands for Non-Equilibrium Dynamic Urban Model, where the term “non-equilibrium” refers to the adjustment process between any two periods.

## 5.1. Introduction

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Here, we address the three aforementioned challenges with the proposal of a LUTI model for Cape Town that builds on a polycentric version of the NEDUM model. To account for the key features of Cape Town, a highly unequal city with a large informal housing sector and a history of subsidized housing provision, we also introduce heterogeneous income groups in the model, as well as informal housing situations that coexist with market and state-driven formal housing.

Our modeling approach builds on a handful of theoretical papers that previously adapted the standard urban land-use model to South African cities (Brueckner, 1996; Selod and Zenou, 2003) or that proposed ways to model a spatial equilibrium in the presence of interacting formal and informal land and housing markets (Brueckner and Selod, 2009; Cai et al., 2018; Selod and Tobin, 2018). The important feature common to all these models is that households can make constrained choices whether to occupy land formally or informally so that an equilibrium relation emerges between the price and extent of formal housing and the size of the informal housing sector.<sup>4</sup> In our framework, we consider two types of land and housing informality: informal settlements in predetermined locations (which is akin to squatting as in Brueckner and Selod, 2009) and a rental market for backyard structures erected by owners of state-driven subsidized housing as recently modeled by Brueckner et al. (2018). We integrate these elements in a closed-city model with exogenous population growth and simulate developers' construction decisions as well as the housing and location choices of households from different income groups at a distance from several employment subcenters (while accounting for state-driven subsidized housing programs, natural constraints, amenities, zoning, transport options, and the costs associated with each transport mode). To our knowledge, our framework is the first two-dimensional urban economics spatial simulation tool to model the internal residential structure of a city with endogenously determined informal housing.<sup>5</sup> As a proof of concept, we conduct "what-if" evaluations of policy scenarios, investigating the spatial consequences of policies relevant to the city of Cape Town. We first simulate the impact of an urban growth boundary adopted by Cape Town's metropolitan planning authority to limit sprawl. The second policy we simulate is the continuation of the ongoing subsidized housing program at varying rates of implementation, asking ourselves whether or not this will be sufficient to significantly reduce housing informality in the city.<sup>6</sup> Our simulations show the long term spatial effects and trade-offs in terms

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<sup>4</sup>Note that housing informality was first modeled by Jimenez Jimenez (1984) and Jimenez (1985) in a partial equilibrium setting. For a review of these models, see Brueckner and Lall (2015).

<sup>5</sup>For a calibrated simulation model with housing informality but no internal city structure see Cavalcanti et al. (2019). For a city-system model of slums, see Alves (2016). For an agent-based model of slums, see Patel et al. (2012). For a dynamic simulation of slums with exogeneous price variations, see Henderson et al. (2016). For a monocentric version of the NEDUM model in a developing country but with no informal housing, see Avner et al. (2017). For city-structure simulations with both endogenous job and residence locations but without explicit consideration of informal land uses, see Ahlfeldt et al. (2015) and Tsivanidis (2018).

<sup>6</sup>To the extent that insecure tenure and associated slum conditions have been shown to entail a range

## 5.2. The Cape Town context

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of footprint reduction versus housing affordability.

In section 5.2 below, we briefly present relevant Cape Town stylized facts regarding job locations (polycentrism), the high level of income inequality that prevails in the city, and the different housing submarkets that coexist. Section 5.3 then details the theoretical model. Section 5.4 presents the data and calibration. Section 5.5 describes a benchmark simulation and the effects of the two sets of policies. Section 5.6 briefly concludes.

## 5.2 The Cape Town context

Cape Town is a sprawling middle-income city of 4.2 million residents, with an ethnically diverse population.<sup>7</sup> The city faces a population growth of 2.4% annually, mostly fueled by in-migration from South African rural areas and other African countries. It has inherited high levels of poverty and acute income inequality (which is highly correlated with race) from past Apartheid policies: As a result, the Gini index for Cape Town is among the highest in the world, reaching .62 in 2017.

This high level of inequality is associated with a fragmented housing market, consisting of four main segments: (i) privately developed formal housing (which houses 52% of residents in 2016), (ii) State-subsidized formal housing (29%), (iii) informal structures in informal settlements (9%), and (iv) structures erected illegally in the backyards of formal housing, mainly State-subsidized housing (8%) (source: Statistics South Africa). Informal settlements first appeared in Cape Town with the rapid urbanization of Black Africans that was stimulated by the labor demands of the war-time economy in the late 1940s (Wilkinson, 2000). They re-appeared at scale during the 1970s as a result of inadequate affordable housing provision coupled with the relaxation of Apartheid-era “influx control laws” (which sought to limit internal in-migration of rural Black Africans to cities). As in the rest of South Africa, housing in informal settlements in Cape Town is characterized by small one-story structures made of corrugated iron sheeting and packed at relatively high densities on peripheral, publicly-owned land originally reserved for future roads, social facilities or public housing. The same type of housing can be encountered as backyard structures although these backyard structures may also be made of brick and mortar. Backyarding was historically a non-transactional, kin-based arrangement first associated with Council housing rolled out for households of Mixed Descent in the 1950s and 1960s. Its proliferation as a housing market accelerated in earnest, along-

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of harmful effects (including e.g., removing workers from the labor force, reducing education and health outcomes, and more generally, a loss in efficiency from the misallocation of land), reducing the level of housing informality in a city can be a justified policy objective. Note, however, that completely eradicating informality may not necessarily be desirable in a second best setting where formalization is very costly as moderate levels of slums may provide the poor access to urban economic opportunities in excess of the negative externalities they generate (see Cai et al. (2018), who derive this result by contrasting *laissez-faire* and social planner equilibria in a spatial dynamic stochastic setting).

<sup>7</sup>In 2011, the population of the metropolitan area was composed of 46% Black Africans, 40% “Coloured” (Mixed Descent), 13% Whites and 1% Indians/Asians (source: census 2011).

## 5.2. The Cape Town context

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side informal settlements, in the wake of large-scale state-driven housing programs from the 1980s onwards, such as the Reconstruction and Development Plan (RDP) in 1994 and, more recently, with the Breaking New Ground (BNG) program (Lemanski, 2009). Both programs aimed to allocate individual, free-standing dwellings by means of full capital subsidy to eligible households (Landman and Napier, 2010). These capital subsidies are allocated in the form of conditional grants by national government to provincial housing departments, with whom the mandate for public housing delivery reside. In the case of large cities, the cost of supportive infrastructure (e.g. roads, services, etc.) are funded by infrastructure grants disbursed by national government directly to metropolitan authorities. Following transfer, additional rooms were in many cases constructed in the backyard, without regulatory approval, from either temporary or permanent building material, often in order to rent these out as an income-generating activity.

In terms of spatial structure, Cape Town is a highly segregated city along income (and racial) lines, with the poor mainly residing to the South East of the City, often far from jobs, which are mainly concentrated in a small number of employment areas in the CBD and along two transport corridors (see Wainer, 2016). Figure 1 below shows the City of Cape Town's built up area, along with major roads and the main employment subcenters.

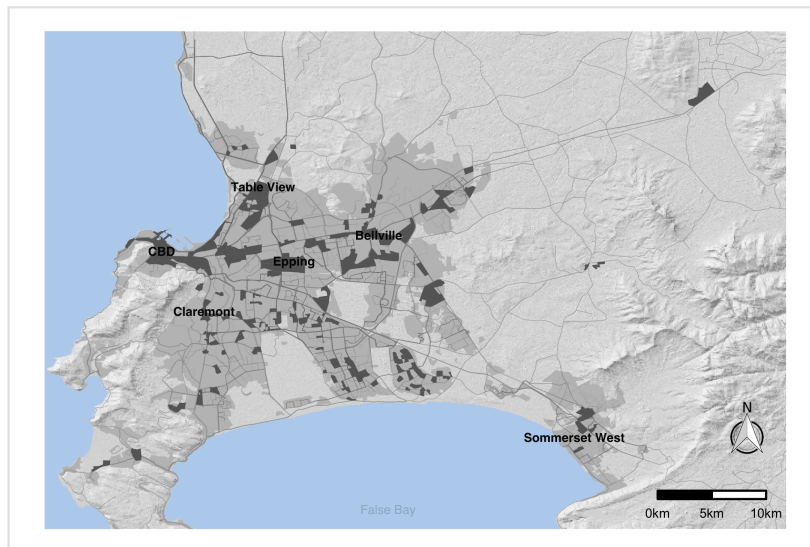


Figure 1: Cape Town's Urban Extent and Employment Centers

Note: The subdivisions on the map are Transport Zones as defined by the City of Cape Town. Transport Zones in dark gray have an employment density above 5,000 jobs/km<sup>2</sup>. The urban extent is represented in gray. Source: City of Cape Town (2013).

### 5.3. The model

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## 5.3 The model

The model focuses on competition for residential land among different housing types.<sup>8</sup> For simplicity, let us first describe the static version of the model (see sections 5.3.1-5.3.3 below) before explaining how dynamics are generated (see section 5.3.4).

### 5.3.1 General assumptions and model intuition

**Land availability and amenities** We consider a 2-dimensional city made of discrete locations within a rectangle that encompasses the whole metropolitan area. Each cell is indexed by an index  $i$  and has an exogenous quantity of available land for residential development  $L_i$ .  $L_i$  varies with  $i$  to account for both natural, regulatory constraints, infrastructure and other non-residential uses. In addition, each location has an exogenous quantity  $A_i$  of natural and historical amenities.

**Job centers, commuting and net income** The city is inhabited by  $N$  households (closed city assumption) divided into 4 skill/income groups (indexed by  $i$ ). Each group has an exogenous number of households  $N_g$  and each household has one worker and other family members. There are  $C$  employment locations in the city, indexed by  $c = 1, \dots, C$ .<sup>9</sup> If considering employment in  $c$ , a worker of group  $g$  could earn a wage  $w_{gc}$  and would have expected income  $y_{gc} = \chi_g w_{gc}$ , where  $\chi_g$  is the exogenous employment rate prevailing in group  $g$ .<sup>10</sup> There are  $M$  possible modes of transportation in the city, denoted by  $m$ . For each residential location  $i$ , job center  $c$ , income group  $g$ , worker  $j$  and mode  $m$ , the expected commuting cost is:  $t_{mjic}(w_{gc}) = \chi_g (\tau_{mic} + \delta_{mic} w_{gc}) + \varepsilon_j$ , where  $\chi_g \tau_{mic}$  is the expected monetary cost of using transport mode  $m$  to travel from  $c$  to  $i$  (accounting for the expected frequency of commuting),<sup>11</sup>  $\chi_g \delta_m w_{gc}$  is the expected cost associated with the time spent commuting, assumed to be proportional to the wage  $w_{gc}$  (opportunity cost of time), and  $\varepsilon_j$  is a random term that follows a Gumbel minimum distribution of mean 0 and scale parameter  $1/\lambda$ .

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<sup>8</sup>The model does not focus on how firms and households may compete for urban space as it considers that the locations of firms and the use of land by firms are exogenous parameters. In practice, anyway, it is noticeable that residential areas occupy more than four times as much space as employment centers in Cape Town.

<sup>9</sup>Note that our framework can account both for polycentric (if  $C > 1$ ) and monocentric cases (if  $C = 1$ ).

<sup>10</sup>This approach can account for stark variations in employment and in wages across skill groups (with low skill workers earning lower wages and being more unemployed than the high skill workers), as well as moderate variations in wages within groups (which entirely stems from differences in labor remuneration across employment centers). For simplicity, and in spite of within-group income heterogeneity, in the rest of the text, we refer to groups  $g = 1, \dots, 4$  as “income groups”, with  $g = 1$  the poorest, and  $g = 4$  the richest.

<sup>11</sup>Note that, with workers potentially cycling in and out of employment, the employment rate also gives the fraction of time spent employed and thus the frequency of commuting.

### 5.3. The model

Commuters choose the mode that minimizes their transport cost. By property of the Gumbel distribution, we can thus write the commuting cost between  $i$  and  $c$  as:

$$\min_m (t_{mjic}(w_{gc})) = -\frac{1}{\lambda} \log \left( \sum_{m=1}^M \exp[-\lambda \chi_g (\tau_{mic} + \delta_{mic} w_{gc})] \right) + \eta_j \quad (5.1)$$

where  $\eta_j$  also follows a Gumbel minimum distribution of mean 0 and scale parameter  $1/\lambda$ . Given their residential location  $i$ , workers choose their workplace location  $c$  that maximizes their income net of commuting costs and solve the program  $\max_c [y_{gc} - \min_m (t_{mjic}(w_{gc}))]$ . The probability to choose to work in location  $c$  given residential location  $i$  and income group  $g$  is therefore given by the following equation:<sup>12</sup>

$$\pi_{c|ig} = \frac{\exp \left[ y_{gc} + \frac{1}{\lambda} \log \left( \sum_{m=1}^M \exp[-\lambda \chi_g (\tau_{mic} + \delta_{mic} w_{gc})] \right) \right]}{\sum_{k=1}^C \exp \left[ y_{gk} + \frac{1}{\lambda} \log \left( \sum_{m=1}^M \exp[-\lambda \chi_i (\tau_{mik} + \delta_{mik} w_{ik})] \right) \right]}. \quad (5.2)$$

We denote  $\tilde{y}_{ig}$  the expected income (over all possible employment centers) net of commuting costs for residents of group  $g$  living in location  $i$ , that is:

$$\tilde{y}_{ig} \equiv \mathbf{E} \left[ y_{gc} - \min_m (t_{mic}(w_{gc})) \mid i \right] \quad (5.3)$$

We can calculate  $\tilde{y}_i$  using (5.1) and (5.2), which gives:

$$\tilde{y}_{ig} = \sum_{c=1}^C \left[ \pi_{c|ig} \left( y_{gc} + \frac{1}{\lambda} \log \left( \sum_{m=1}^M \exp[-\lambda \chi_g (\tau_{mic} + \delta_{mic} w_{gc})] \right) \right) \right] \quad (5.4)$$

From equation (5.2), we can derive the expected number of residents of income group  $g$  choosing to work in  $c$ , denoted  $W_{gc}$ , providing that we know the number of residents of income group  $g$  with their residence in  $i$ , denoted  $N_{ig}$ , in all  $i$ . We have:

$$W_{gc} = \chi_g \sum_i \left[ \frac{\exp \left( y_{gc} + \frac{1}{\lambda} \log \left( \sum_{m=1}^M \exp[-\lambda \chi_g (\tau_{mic} + \delta_{mic} w_{gc})] \right) \right)}{\sum_{j=1}^C \exp \left( y_{gj} + \frac{1}{\lambda} \log \left( \sum_{m=1}^M \exp[-\lambda \chi_g (\tau_{mij} + \delta_{mij} w_{gj})] \right) \right)} N_{ig} \right] \quad (5.5)$$

**Housing types** There are potentially four types of housing, generically denoted  $h$ . The four categories include  $h = FP$  (“formal private”) for housing formally provided by the private sector,  $h = FS$  (“formal subsidized”) for housing delivered under a subsidized-housing program such as the RDP or BNG, and two types of informal housing:  $h = IS$

<sup>12</sup>Note that although our modeling differs from the random-utility approach (see Anas and Liu, 2007) and from the match-productivity approach (see Ahlfeldt et al., 2015; Tsivanidis, 2018), all yield similar types of gravity equation such as (5.2).

### 5.3. The model

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(“informal settlement”) for housing in an informal settlement, and  $h = IB$  (“informal backyard”) for housing in a backyard structure of a plot that was initially delivered under a subsidized-housing program.<sup>13</sup> As will be detailed below, subsidized housing is accessed outside a market-determined price (see below) but a market exists for formal private housing ( $h = FP$ ) as well as for informal backyard structures ( $h = IB$ ) and for informal settlement structures ( $h = IS$ ).<sup>14</sup>

In line with empirical observations, we assume that the set of housing options varies across income groups, with only the lowest income groups considering the possibility of informal housing. In our framework, individuals from income group 1 (the poorest) are eligible for public housing. Only a fraction of individuals from this income group, however, will benefit from the relatively small amount of housing provided under the public housing program. The other individuals in this income group will be rationed out and may decide to live in informal settlements, in other people’s backyards, or in formal private housing. Individuals from income group 2 (the second poorest group) face the same housing choices as individuals from income group 1 but are not eligible for public housing which only targets the poorest individuals. Finally, income groups 3 and 4 (the richest groups) may only be housed in formal private housing.<sup>15</sup>

These assumptions are summarized in Table 5.A.2 in appendix 5.A.

**Utilities** The type and quantity of housing consumed affect household utility. In our model, households derive utility by consuming a composite good  $z$ , housing quantity  $q$ , and facing amenities  $A$  and a housing type externality  $B^h$ , where  $h = FP, FS, IS, IB$ . As in chapter 3, we use a Stone-Geary specification for utility. Household utility is:

$$U(z, q, A, h) = z^\alpha (q - q_0)^\beta A B^h, \quad (5.6)$$

where  $q_0 > 0$  is the minimum need for housing quantity,  $\alpha + \beta = 1$ , and  $B^{FP} = B^{FS} = 1$  and  $B^{IS}$  and  $B^{IB} < 1$ .

Because  $B^h$  is a multiplicative term in the utility function, the condition  $B^{FP} = B^{FS} = 1$  means that there is no externality associated with formal housing, whereas  $B^{IS}$

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<sup>13</sup>Note that no central, authoritative registry of public housing is available in Cape Town documenting all housing delivered under the succession of government programs that were implemented since the 1920s (Wilkinson, 2000). Earlier public housing varies greatly in terms of typology, tenure arrangement and quality, and some of it has subsequently re-entered the formal housing market. For the purpose of this model, a series of explicit neighborhood, zoning, and physical attributes were used to delineate public housing characteristic of the RDP and BNG housing programs from overall housing stock in existence today.

<sup>14</sup>Although local surveys suggest that a significant proportion of beneficiaries resell the properties that were initially allocated to them under subsidized-housing programs (Tissington et al., 2013), for simplicity, we do not model this secondary market. Because the sales likely remain within the same income group, this has no impact on income sorting in the model.

<sup>15</sup>Although income groups 3 and 4 face similar housing choices, we distinguish between these two groups in order to better account in our simulations for income heterogeneity and spatial sorting along income lines.

### 5.3. The model

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and  $B^{IB} < 1$  capture the negative externalities associated with informal housing (Galiani et al., 2017). It can easily be shown that the Stone-Geary specification also implies that the rich will value more than the poor residing in locations with better amenities (as in Brueckner et al., 1999).

Having laid out these general assumptions, we can now say a few words about the functioning of the model: Housing will be provided exogenously by the government in the form of limited subsidized housing in areas of the city zoned for such developments, and endogenously by competitive developers (for formal private housing), by illegitimate absentee 'landowners' (for informal settlements) and by beneficiaries of subsidized-housing (for backyard structures). Those among low-income households who are not granted subsidized housing (a fraction of income group 1 households and all of income group 2 households) will compete for locations within and across the different market segments (formal private, informal settlements and backyards), with housing being allocated to the highest bidder in each market segment.<sup>16</sup> In the subsection below, we begin by deriving the demand and supply for the different housing types before presenting the equilibrium in the subsection that follows.

#### 5.3.2 Housing markets

##### Housing supply

In each location  $i$ , the total quantity of available land (free of constraints) is exogenously given by  $L_i$ . This amount is further broken down into land available for each primary housing type, denoted  $L_i^h$  for  $h = FP, FS, IS$ . In our framework, because informal settlement locations vary little over time and because the quantity of land allocated to subsidized housing is a policy decision,  $L_i^{FS}$  and  $L_i^{IS}$  are exogenously given. This implies that the quantity of land available for private formal development is also exogenous and given by the residual:

$$L_{i,FP} = L_i - L_i^{FS} - L_i^{IS} \quad (5.7)$$

As will be detailed below, the fraction of subsidized-housing land allocated to backyarding will be endogenously determined.

The number of individuals residing in each housing type,  $N_i^h$  for  $h = FP, FS, IS, IB$  and the overall number of individuals residing in each location,  $N_i (= \sum_h N_i^h)$  are also endogenous quantities.

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<sup>16</sup>Observe that although there is competition for land within each market segment, there is no *direct* competition for land across market segments in the sense that households choosing to reside in one type of housing do not need to outbid households choosing to reside in another type of housing. This stems from the fact that the locations of informal settlements and of subsidized-housing programs—where backyarding occurs—are exogenously given. Households from income groups 1 and 2 can nevertheless decide in which market segment to demand land, increasing or decreasing the demand for land in the different market segments accordingly.



### 5.3. The model

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Below, we derive the supply of each housing type in a given location  $i$ .

**Formal private housing** Let us start with presenting the supply of formal housing by competitive developers. In a location  $i$ , a developer will purchase land at a price  $P_i$  from absentee landlords and will combine land with capital to produce housing, before renting out housing to individuals at a price  $R_i^{FP}$ . Note that both prices  $P_i$  and  $R_i^{FP}$  will be determined in equilibrium but for the time being, we consider them as given and express housing supply conditional on these prices. As standard in the developer model (see Fujita, 1989), the housing surface built,  $S^{FP}$ , is given by a production function with constant returns to scale:  $S^{FP}(K, L) = \kappa L^a K^{1-a}$ , where  $0 < a < 1$  is the land elasticity of housing production,  $L$  is the land surface occupied by the building,  $K$  is the capital used for development, and  $\kappa$  is a scale parameter.<sup>17</sup> We express the quantity of housing produced per unit of land as:

$$s^{FP}(k) = \kappa k^{1-a}, \quad (5.8)$$

where  $k = K/L$  is the capital per unit of land.

For a developer, the profit per land unit in location  $i$  is thus:

$$\Pi_i(k) = R_i^{FP} s^{FP}(k) - k(\rho + \delta) - (\rho + \delta)P_i \quad (5.9)$$

where  $\rho$  is capital depreciation and  $\delta$  is the cost of capital.

Profit maximization with respect to capital per unit of land yields the solution:

$$k = \left( \frac{\kappa(1-a)R_i^{FP}}{\rho + \delta} \right)^{\frac{1}{a}} \quad (5.10)$$

and

$$s_i^{FP} = \kappa^{\frac{1}{a}} \left( \frac{(1-a)R_i^{FP}}{\rho + \delta} \right)^{\frac{1-a}{a}} \quad (5.11)$$

Note that equation (5.11) expresses the supplied housing quantity per unit of land in location  $i$  as a function of the market-determined rent for formal private housing in that location.<sup>18</sup>

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<sup>17</sup>The literature is split regarding the specification to use for housing production functions. The practices in the US has long been to use a Constant Elasticity of Substitution (CES) specification with an elasticity of substitution lower than 1, implying that the ratio of capital to land value decreases with distance to the city center (see Larson and Yezer, 2015). Recent papers for the US and France, however, have concluded that a Cobb-Douglas function (implying an elasticity of substitution equal to 1) is a good approximation (see Epple et al., 2010; Combes et al., 2017).

<sup>18</sup>Using the zero profit condition, the price of land paid by developers to absentee landlords is also a function of the price of housing sold by developers to individuals, with  $P_i = a(1-a)^{\frac{1-a}{a}} \left( \frac{\lambda R_i^{FP}}{\rho + \delta} \right)^{\frac{1}{a}}$ .

### 5.3. The model

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In location  $i$ , the total quantity of supplied formal private housing will be  $S_i^{FP} = s_i^{FP} L_i^{FP}$ .<sup>19</sup>

**Formal subsidized housing** Let us now turn to the supply of subsidized housing (RDP and BNG programs). For simplicity, in our framework, subsidized housing is exogenously supplied for free to a limited number of individuals among income group 1 (the low-income group).<sup>20</sup> Each plot in the single-family subsidized housing scheme is of fixed size  $q^{FS}$ , including a backyard of fixed size  $Y$ . As we will see below, occupants of subsidized housing may decide to rent out a fraction  $\mu_i < 1$  of their backyard, so that the remaining quantity of housing that they end up consuming is  $q^{FS} - \mu_i Y$ .

**Informal housing in backyards** We adopt here a simplified version of the “backyarding model” recently proposed by Brueckner et al. (2018). In our setting, some individuals from income group 1 will be granted subsidized housing for free. The other individuals from income groups 1 and 2 may decide to reside informally in backyard structures, paying a rent  $R_i^{IB}$  per unit of housing (to be determined in equilibrium) to beneficiaries of subsidized housing.

In each location  $i$ , the fraction of backyard space rented out  $\mu_i$  is chosen to maximize the utility of subsidized housing beneficiaries,

$$U(z, q^{FS} - \mu_i Y, A, 1) = z^\alpha (q^{FS} - \mu_i Y - q_0)^\beta A, \quad (5.12)$$

under the budget constraint:<sup>21</sup>

$$\tilde{y}_{i1} + \mu_i Y R_i^{IB} = z. \quad (5.13)$$

The first-order condition leads to:

$$\mu_i = \alpha \frac{q^{FS} - q_0}{Y} - \beta \frac{\tilde{y}_{i1}}{Y R_i^{IB}}. \quad (5.14)$$

Note that  $\mu_i$  increases with  $R_i^{IB}$ , which replicates a result from Brueckner et al. (2018) under well-behaved properties of the utility function, all things else equal, a higher rental price for backyard structures will increase the supply of backyard housing.<sup>22</sup>

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<sup>19</sup>We abstract from modeling the construction and funding of infrastructure networks (water, electricity, transport) to support spatial urban expansion. Infrastructure network expansion costs could be considered in the model as additional costs borne by private developers through impact fees, or as a cost collectively funded by city residents under a property tax.

<sup>20</sup>Subsidized housing could be provided at a non-zero price without significantly altering the results of the model.

<sup>21</sup>Observe that all subsidized housing beneficiaries belong to income group 1, hence the notation  $\tilde{y}_{i1}$  to denote income net of commuting costs.

<sup>22</sup>With a general utility function, the effect of land rents on backyard space rental is ambiguous because the increment in income associated with higher rents (which tends to decrease the rental of backyard space) plays in the opposite direction of the substitution effect associated with a greater opportunity

### 5.3. The model

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The quantity of backyard housing in location  $i$  will thus be  $S_i^{IB} = \mu_i Y N_i^{FS}$ , where  $N_i^{FS}$  is the exogenous number of subsidized dwellings in location  $i$ .

**Informal settlements** Zones where informal settlements occur are exogenously determined in the model (accounting for historic locations) so that the maximum supply of informal settlement land in a location  $i$  is  $L_i^{IS}$ . Individuals residing in informal settlements pay a rent  $R_i^{IS}$ , even though this payment is not made to the legitimate owner of the land (see Brueckner and Selod, 2009, for a description of squatting arrangements and associated payments). In our setting, the rent extracts informal settlers' willingness to pay for living in an informal settlement given the negative externality and the fixed size of informal structures  $q^I$ . For simplification, we assume that it does not cost anything to build an informal structure and that no capital investment is required (as informal structures only have one floor, i.e. a floor-area ratio of 1) so that it is not necessary to model the building decisions of illegitimate absentee 'owners' of informal settlement. This implies that in location  $i$ , given the quantity of land  $L_i^{IS}$  available for informal settlers, there can be at most  $L_i^{IS}/q^I$  informal settlement structures.

#### Housing demand

Before deriving the demand for the different housing types, note that the budget constraint of a household of income group  $g$ , and residing in location  $i$ , under housing type  $h$  can be written as:

$$\tilde{y}_{ig} + \mathbf{1}_{\{h=FS\}} \mu_i Y R_i^{IB}(\mathbf{x}) = z + q^h R^h \quad (5.15)$$

where  $\mathbf{1}_{\{h=FS\}}$  is the indicator function equal to 1 for occupants of subsidized housing (as these households have rental income  $\mu_i Y R_i^{IB}$ ) and equal to 0 for everyone else, and  $R^h$  is the rent per unit of housing of type  $h$  (with  $R^{FS} = 0$ ).

Below, we derive the demand for housing conditional on location  $i$  and on each housing type  $h$ , starting with formal private housing.

**Formal private housing** For a given location  $i$ , an urban resident will demand a quantity of housing that maximizes utility (5.6) under constraint (5.15) and the minimum dwelling size condition  $q^{FP} \geq q_{min}$ .<sup>23</sup> This yields the following first-order conditions:

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cost of own yard space consumption (which tends to increase the rental of backyard space). In theory, the supply of backyard housing could thus decrease if the former effect dominates the latter. Brueckner et al. (2018), however, show that a standard utility function, such as the Cobb-Dougllass, rules out this possibility altogether.

<sup>23</sup>Note that the minimum dwelling size  $q_{min}$  is different from the basic housing need  $q_0$  that we introduced earlier in the utility function (with  $q_{min} \geq q_0$ ).

### 5.3. The model

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$$\begin{cases} q^{FP} R^{FP} &= \beta \tilde{y}_{ig} + \alpha q_0 R^{FP} \\ z &= \alpha \tilde{y}_{ig} - \alpha q_0 R^{FP} \\ q^{FP} &\geq q_{min} \end{cases} \quad (5.16)$$

Because we have a minimum dwelling-size condition, we solve the system as follows: Let us denote  $Q_{ig}^*$  and  $Z_{ig}^*$  the optimal quantity of formal housing and composite good that households would want to consume in the absence of a minimum dwelling size requirement. Rearranging terms from the first two conditions in system (5.16) and plugging them into equation (5.6), we can express utility as:

$$u = \alpha^\alpha (\tilde{y}_{ig})^\alpha \frac{Q_{ig}^* - q_0}{(Q_{ig}^* - \alpha q_0)^\alpha} A_i B^{FP} \quad (5.17)$$

This implicitly defines  $Q_{ig}^*$  as a function of  $u$ . Note that, because  $\alpha < 1$ ,  $u$  increases with  $Q_{ig}^*$ , which implies that  $Q_{ig}^*(u)$  is an increasing function of  $u$ . Because the SOC is verified (given that  $\alpha$  and  $\beta < 1$ ), it is then easy to see that the constrained housing demand (i.e., the housing demand that is potentially constrained by the minimum dwelling-size condition) is  $Q_{ig}^{FP}(u) = \max(q_{min}, Q_{ig}^*(u))$ .

Plugging back  $Q_{ig}^*(u)$  into the first condition in system (5.16) and inverting the resulting equation in the rent gives the bid rent:

$$\psi_{ig}^{FP}(u) = \frac{\beta \tilde{y}_{ig}}{Q_{ig}^{FP}(u) - \alpha q_0}, \quad (5.18)$$

which expresses the maximum rent a household from group  $g$  would be ready to pay to reside in private formal housing in location  $i$  in order to attain utility  $u$ .

From equation (5.17), we can see that  $Q_{ig}^{FP}(u)$  is an increasing function of  $u$ , a decreasing function of  $A_i$ , and a decreasing function of  $\tilde{y}_{ig}$ . Therefore, the bid-rent  $\psi_{ig}^{FP}(u)$  is an increasing function of  $A_i$ , and an increasing function of  $\tilde{y}_{ig}$ . This implies that the bid-rent will be greater in locations with high amenities, and good accessibility to jobs. From equation (5.11), the quantity of housing produced per unit of land is an increasing function of rents, therefore it will also be greater in those locations.

**Formal subsidized housing** Formal subsidized housing is offered in overall quantity  $N^{FS} = \sum_i N_i^{FS}$  to a fraction of income group 1 households. The “demand” for subsidized housing will thus involve rationing as long as  $N^{FS} < N_1$ .<sup>24</sup> Note that the utility of a subsidized-housing recipient residing in  $i$  is:

$$U(\tilde{y}_{i1} + \mu_i Y, q^{FS} - \mu_i Y, A, 1) = (\tilde{y}_{i1} + \mu_i Y)^\alpha (q^{FS} - \mu_i Y - q_0)^\beta A_i \quad (5.19)$$

<sup>24</sup>Note that, in the model, beneficiaries of subsidized housing have the option to reject the offer (see the equilibrium definition in Section 3.3). In practice and in our simulations, however, subsidized housing is sufficiently advantageous for all beneficiaries to always accept the offer.

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**Informal housing in backyards** Backyard structures have a fixed size,  $q^I$ . Because individuals in backyard structures will spend all their income net of commuting and housing costs on the composite good, a household residing at location  $i$  obtains utility:

$$u = (\tilde{y}_{ig} - q^I R^{IB})^\alpha (q^I - q_0)^\beta A_i B^{IB}. \quad (5.20)$$

Inverting equation (5.20) in the land rent gives the following bid rent:

$$\psi_{ig}^{IB}(u) = \frac{1}{q^I} \left( \tilde{y}_{ig} - \left[ \frac{u}{(q^I - q_0)^\beta A_i B^{IB}} \right]^{1/\alpha} \right). \quad (5.21)$$

As in the case of formal private housing, the above formula measures the maximum rent an income group  $g$  household would be willing to pay for backyard housing in  $i$ , while commuting to  $c$ , in order to attain utility  $u$ . Because the income net of commuting  $\tilde{y}_{ig}$  decreases when moving away from jobs, it is easy to see from (5.21) that a household will be willing to pay more to reside in a backyard structure located closer to jobs. The supply of backyard structures will in turn positively respond to these higher bids as can be seen in equation (5.14).<sup>25</sup>

**Informal settlements** Finally, the same reasoning applies to the demand for informal settlement housing, leading to the following bid rent:

$$\psi_{ig}^{IS}(u) = \frac{1}{q^I} \left( \tilde{y}_{ig} - \left[ \frac{u}{(q^I - q_0)^\beta A_i B^{IS}} \right]^{1/\alpha} \right) \quad (5.22)$$

which measures the maximum payment a household of income group  $g$  would accept to pay to obtain utility  $u$  while residing in an informal settlement in  $i$  and commuting to  $c$ .<sup>26</sup>

#### 5.3.3 The static equilibrium

We can now define an equilibrium as follows:

**Definition 22.** *An equilibrium is the set  $\{u_g; N_{ig}^h; R_i^h; S_i^h; W_{gc}\}$ , for all  $i, h$  and  $g$  (where these functions are defined), where:*

<sup>25</sup>In theory, because subsidized-housing beneficiaries will also obtain a higher wage income net of commuting costs from a closer location to jobs, the supply response to higher rents closer to jobs can be ambiguous because of the additional income effect discussed in footnote 18 (mathematically, see the  $\tilde{y}_{i1}$  term in 5.14). Brueckner et al. (2018) show that if subsidized-housing beneficiaries are less attached to the labor market (i.e., if they commute less) than backyard structure renters, then  $\mu_i$  will be greater in locations with greater job accessibility. The condition is verified in our case as subsidized-housing beneficiaries belong to group 1 which has the lowest employment rate.

<sup>26</sup>Observe that the bid rents for backyarding and informal settlement dwellings are identical, except for the housing externality term.

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- $u_g$  is the utility of income group  $g$ ;
- $N_{ig}^h$  is the distribution of households of income group  $g$ , housed in housing type  $h$ , and residing in  $i$ ;
- $R_i^h$  is the market rent of housing type  $h$  in  $i$  where these housing types are present, i.e. for  $i \in X_h = \{i \mid N_h = \sum_g N_{ig}^h > 0\}$  and  $h \in \{FP, IB, IS\}$ ;
- $S_i^h$  is the quantity of each housing type  $h$  in  $i$ ;
- $W_{gc}$  is the number of workers from group  $g$  working in  $c$ .

and satisfying the following constraints:

1.  $N_g = \sum_h \sum_i N_{ig}^h$ ;
2.  $P_i \geq P_A$  for  $i \in X_{FP}$ ;
3.  $u_{ig}^h = u_g$  for all  $h \in H_{ig} = \{h \neq FS \mid N_{ig}^h > 0\}$ ;
4.  $N_{ig}^h = \begin{cases} 0 & \text{if}(g) \neq \text{Argmax}(\psi_{ig}^h(u_g)) \\ S_i^h L_i^h / Q_{ig}^h(u_g) & \text{if}(g) = \text{Argmax}(\psi_{ig}^h(u_g)) \end{cases}$  for all  $i$ , and for  $h = FP, IB, IS$ ;
5.  $\sum_{c=1}^C W_{gc} = \sum_i \chi_g N_{ig}$

Note that (i) is a set of population constraints (which ensure that the city hosts all individuals in equilibrium). (ii) is a city-edge constraint (which reflects the indifference of absentee landlords at the city fringe between selling their land to a developer or engaging in agricultural activities). (iii) is a set of utility equalization constraints (which reflects indifference among individuals of each income group between locations and housing types). This utility equalization constraint does not involve beneficiaries of formal subsidized housing, as they benefit from a windfall transfer from the State and will have a higher equilibrium utility than non-beneficiaries in their income group.<sup>27</sup>

(iv) ensures that land is allocated to the highest bidder for each housing type in each cell (with the exception of subsidized housing beneficiaries who do not compete for land with anyone), and that housing demand and housing supply are equated in each location.

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<sup>27</sup>Note that, in equilibrium, we allow households to decline the subsidized housing they are offered and decide to live in an informal settlement, in a backyard structure, or in the private housing sector instead. If the utility from residing in a subsidized housing location is lower than for other housing types, then the household would be better-off declining the offer and the housing unit will remain vacant. In practice, however, this is very unlikely to happen given the advantageous conditions (free rent, relatively large dwelling, and possibility of renting out the backyard) under subsidized housing.

### 5.3. The model

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<sup>28</sup> Note that *(iv)* reflects competition for land within submarkets but not directly across market segments. Finally *(v)* ensures labor-market clearing.

Observe that in equilibrium, formal and informal housing markets are connected in several ways. Firstly, there is a direct connection due to the fact that, with the exception of subsidized-housing beneficiaries who receive a transfer from the State, other poor households from income group 1 and from income group 2 optimize across formal and informal residential options until their utilities are equalized (constraints *(iii)* and *(iv)* in the equilibrium definition). Secondly, the fact that informal settlements and backyarding locations are exogenously determined does not imply that formal and informal housing developments occur in isolation of one another. In fact, they are linked through the choices of poor households across formal and informal housing options, and because formal developers' building decisions respond to private formal housing prices (see equation 5.11 and constraint *(iv)* in the equilibrium definition), with private formal housing prices partially reflecting the sorting of low-income households across formal and informal housing market segments. Finally, there is an externality associated with the use of land for informal settlements and for publicly subsidized housing as these areas are somehow taken away from developable land that would otherwise be available for private formal development (see the land-use accounting equality 5.7). This affects the supply and demand for formal housing by restricting the set of potential locations available for private formal development, while accommodating a potentially large number of urban residents in the informal sector.<sup>29</sup>

**Existence and uniqueness of equilibrium** Although the model is simple and has clearly laid-out supply and demand mechanisms, it is not possible to solve it analytically and we will resort to numerical simulations. As regards existence and uniqueness, it can be shown that the equilibrium exists and would be unique in the open-city case, as bid-rents, dwelling sizes, housing supply, and therefore population densities, are uniquely defined for given levels of utility. In our closed-city case, however, the unicity of the equilibrium is more complex to derive. Because of potentially non-monotonic residential sorting under a Stone-Geary specification function, one could suspect the possibility of multiple equilibria. In chapter 3, however, we theoretically showed that with two income groups and one housing type, the equilibrium with Stone-Geary utilities is always unique. In our context with four income groups and four housing types, although we do not have a formal proof of equilibrium unicity, it is noticeable that running 250 simulations of our benchmark case (starting from a wide range of starting points), the algorithm always

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<sup>28</sup>Because we assume that only the poor may reside informally, note that  $N_g^{IB} = N_g^{IS} = 0$  for  $g = 3, 4$  (income groups 3 and 4).

<sup>29</sup>The net effect on formal housing prices is ambiguous as the restricted supply of formal land should raise formal housing prices in the center, while pushing away population to peripheral areas where prices will be lower. Housing in the informal sector reduces the demand for formal housing, which exerts a downward pressure on formal housing prices.

### 5.3. The model

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converged to the same equilibrium solution. Although we cannot prove it formally, this strongly suggests that the model has a unique equilibrium.

#### 5.3.4 Dynamics

Before describing how the model can be solved numerically (see section 5.3.5), we first extend it to a dynamic version. In this dynamic version, the system is affected by exogenous variations in inputs over time (for example under a scenario of exogenous demographic changes) and the system responds with adjustments to these exogenous shocks that do not occur instantaneously. More specifically, we assume that the formal housing stock depreciates with time and that formal developers respond to price incentives with delay as in Viguié and Hallegatte (2012).<sup>30</sup>

Mathematically, this implies that the stock of housing at time  $t$ ,  $[S_i^{FP}]_t$  may not equate the theoretical equilibrium quantity,  $[S_i^{FP}]_t^*$ . Denoting  $\tau$  the time lag for construction (*i.e.*, the time needed to complete a housing project) and  $\theta$  the time lag for depreciation (*i.e.*, the time needed for total depreciation of a building), the change in the housing stock between times  $t$  and  $t + 1$  is:

$$[S_i^{FP}]_{t+1} - [S_i^{FP}]_t = \begin{cases} \frac{[S_i^{FP}]_{t+1}^* - [S_i^{FP}]_t}{\tau} - \frac{[S_i^{FP}]_t}{\theta} & \text{if } [S_i^{FP}]_{t+1}^* > [S_i^{FP}]_t \\ -\frac{[S_i^{FP}]_t}{\theta} & \text{if } [S_i^{FP}]_{t+1}^* \leq [S_i^{FP}]_t \end{cases} \quad (5.23)$$

This law of motion reflects developers' investments when the current stock of housing is below the equilibrium and the absence of investment if the reverse is true.<sup>31</sup>

#### 5.3.5 Numerical solution and simulation algorithm

In this subsection, we first present how the static equilibrium is solved in each period. We then describe how the dynamics is implemented.

**Static equilibrium** We apply an iterative algorithm to converge towards a solution. Because we have a close city, the total population for each income group is fixed. Our algorithm then solves for all other variables. We start with an arbitrary set of initial utilities, from which we determine:

1. Housing demand for each housing type, using equation (5.17) for formal housing, and the fact that informal settlement dwellings have a fixed size  $q^I$ ;

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<sup>30</sup>We do not assume such delay for the informal sector, which, in practice, can respond very quickly to changing conditions.

<sup>31</sup>Observe that the theoretical values  $[S_i^{FP}]_t^*$  and  $[S_i^{FP}]_{t+1}^*$  will be equal in the absence of any exogenous variation between  $t$  and  $t + 1$ . The housing stock, however, may adjust so that  $[S_i^{FP}]_t$  and  $[S_i^{FP}]_{t+1}$  are not necessarily equal.



## 5.4. Data sources and parameter calibration

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2. Rents, using equation (5.18) for formal private housing, equation (5.21) for informal backyarding and equation (5.22) for informal settlements;
3. Housing supply, using equation (5.11) for formal housing and equation (5.14) for informal backyarding.
4. Population in all locations for all housing types, using equilibrium condition (*iv*).

By summing populations across locations and housing types, we obtain the total population for each income group. Utilities are then incrementally adjusted and steps 1-4 iterated until the target population allocation is simulated. Graph 5.E.1 in appendix 5.E summarizes the procedure.

**Dynamics** We consider the state of the city in year  $t$ . One year later, at  $t + 1$ , we solve the equilibrium for a new set of input parameters (which may have exogenously changed, for instance if the population has increased). This determines housing supply without private construction inertia. We then apply equation (5.23) to determine the actual formal private housing supply at year  $t + 1$ , accounting for inertia. Dwelling size and prices are then determined by deriving the new equilibrium given the period's housing supply. This determines the new state of the city. We then reiterate the process for subsequent periods.

## 5.4 Data sources and parameter calibration

We apply the theoretical model to a grid of 100 x 80 km that largely encompasses the existing urban footprint of Cape Town. The grid is subdivided into 500m x 500m cells. Each cell represents a location  $i$  in our theoretical framework. Because the different data sets that we use are available at different spatial resolutions, we either spatially aggregated or disaggregated the information using cell areas as weights.

We make use of a variety of data sets as direct inputs into the model and in order to calibrate parameter values. More specifically, the inputs that are fed into the model consist of the total population in the city at an initial date and its decomposition into income groups ( $N_g$ ), the average income and employment rate ( $\chi_g$ ) by income group, land use constraints ( $L_i^h$ ), and the monetary and time cost of commuting ( $\tau_{mic}$ ) and ( $\delta_{mic}$ ) between cells and job centers, for 5 different modes (walking, minibus/taxi, train, bus, private car).<sup>32</sup> Exogenously chosen parameters include the size of subsidized housing plot ( $q^{FS}$ ), the time lag of housing investment ( $\tau$ ), the housing stock depreciation parameter ( $\theta$ ), the financial depreciation rate of built capital ( $\rho$ ), and the agricultural land rent ( $P_A$ ). Estimated parameters include the gravity equation parameter ( $\lambda$ ), wages at workplace ( $w_{gc}$ ), housing consumption elasticity in the utility function ( $\beta$ ), the minimum housing consumption ( $q_0$ ), the land elasticity of housing production ( $a$ ), the scale parameter of

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<sup>32</sup>For simplicity, in what follows, we do not index these variables with time.

## 5.4. Data sources and parameter calibration

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housing production ( $\kappa$ ), and the index value of amenities  $A_i$ . The disutility parameters of informal housing ( $B^{IB}$ ) and ( $B^{IS}$ ) are calibrated to reproduce the distribution between housing types generated by the model.

Below, we describe in more detail data sources and the calibration process.

### 5.4.1 Data sources

The spatial distribution of population is taken from National Censuses for the years 2001 and 2011. We define the four income groups by choosing income-group thresholds such that only the lowest income group is eligible for subsidized housing programs, and so that the two highest income groups are not observed to reside informally (see appendix 5.A for details).<sup>33</sup>

We use the transport model used by the City of Cape Town to retrieve transport times between pairs of transport zones for each transport mode and job locations.<sup>34</sup> We also use aggregate statistics on modal shares and residence-workplace distances in Cape Town, that are derived from Cape Town’s 2013 Transport Survey.

Land availability is defined for each housing type. Areas of subsidized housing are identified from the cadastre of the City of Cape Town.<sup>35</sup> The area available for backyard housing is estimated as the yard size of these units. Informal settlement areas are obtained from the Enumerator Area definition of the 2011 Census. Land available for formal private development corresponds to all land that is not constrained for construction.<sup>36</sup>

The amenities that we consider include natural amenities (such as slope and proximity to the ocean) as well as historical amenities (such as the proximity to the historical center). The data sets used are listed in 5.C.4.

For the estimation of the model’s parameters (see below), we also use property price data extracted from the City of Cape Town’s geocoded data set on property transactions for 2011, as well as data on dwelling sizes made available to us by the City of Cape Town.

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<sup>33</sup>The Census captures annual income, which we assume reflects the employment rate  $\chi_g$ . Households eligible for subsidized housing are the ones with an annual income ( $\chi_g w_{gc}$  in the model) below the threshold of R38,200.

<sup>34</sup>The origin-destination matrix is produced by the City of Cape Town’s four-step travel demand model, last updated in 2013 using the EMME/2 software. The model was designed by INRO Consultants at the University of Montreal and adopted by the City of Cape Town in 1991. The model implements an equilibrium route assignment based on the distribution of trip origins and destinations in relation to the transport network. The model is calibrated by means of the General Household Transport Survey, on-board surveys and cordon counts.

<sup>35</sup>This corresponds to the category ‘Single Residential 2 - Incremental Housing’.

<sup>36</sup>Restrictions include areas used for formal subsidized housing, informal settlements, protected natural areas, large economic or industrial infrastructures (such as the Cape Town airport). A detailed list of sources is presented in 5.B.3.

## 5.4. Data sources and parameter calibration

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### 5.4.2 Estimation of the parameters of the model

The estimation of the model is done in three steps. First, we choose a first set of parameters using available information, without solving the model. These include the minimum dwelling size  $q_{min}$ , the size of subsidized plots  $q^{FS}$  and of backyards  $Y$ , the construction lag  $\tau$ , the physical and financial depreciation of housing  $\theta$  and  $\rho$ , the interest rate  $\delta$ , and the agricultural rent  $R_A$ . The minimum dwelling-size for formal housing is set at  $q_{min} = 31.6 m^2$ , which is the minimum dwelling size observed in formal neighborhoods. Backyards of subsidized houses have a size  $Y = 70 m^2$ . We choose the time lag of housing investment  $\tau$  to be 3 years and the physical depreciation time of building stock  $\theta$  to be 100 years, as in Viguié et al. (2014). The financial depreciation rate of the built capital is  $\rho = .05$  (i.e., 5%). We allow the interest rate  $\delta$  and the agricultural land rent  $P_A$  to vary with time. For  $\delta$ , we use the annual values for South Africa in the World Development Indicator database (World Bank, 2016). We set the agricultural price at the city border  $P_A$  at  $807 Rands/m^2$  (annual) in 2011, which corresponds to the ninth decile in the sales data sets, when selecting only agricultural properties in rural areas. In the dynamic simulations, we assume that the agricultural land is constant in real terms and have its nominal value increase at the same rate as the average household nominal income.

Second, we calibrate wages, housing production function parameters, utility function parameters and amenities using partial relations from our model. Following Ahlfeldt et al. (2015), we recover the vector of wages ( $w_{gc}$ ) using data on job locations and residential locations. The scale parameter in the commuting formula,  $\lambda$ , is estimated using the distribution of residence-workplace distances in Cape Town. We identify the land elasticity of housing production ( $a$ ) and the scale parameter of housing production ( $\kappa$ ) by regressing the log of equation (5.11) (see appendix 5.B for details). We then consider equations (5.16) and (5.18), which relate utility levels to dwelling sizes, rents and amenities. The amenity term,  $A_i$  is expressed as a score for all locations, and specified as  $A_i = \prod_k a_{ik}^{\nu_k}$ , where the  $a_{ik}$  are measures for each amenity type (see 5.C.4), and  $\nu_k$  are their marginal valuation, to be estimated. We simultaneously estimate the system of equations by maximum likelihood and recover parameters  $\{\beta, q_0, \nu_k\}$ . 5.C.4 presents the procedure in more detail.

Third, we calibrate the disutility parameters of informal housing ( $B^{IB}$  and  $B^{IS}$ ) by running the entire model to replicate the share of households in informal settlements and backyard housing in the 2011 Census data.

### 5.4.3 Benchmark simulation and retrospective fit

We run a benchmark simulation to compare the outputs of the model with the data. Past evolution of average income, total population and income distribution are derived from Census data. Results are presented on figure 5.D.1 of appendix 5.D, which graphically shows that the overall fit is reasonable. We run a retrospective simulation (i.e., running

## 5.5. Scenarios and prospective simulations

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the model 'backwards') starting in 2011, and compare the outputs of the model 2001 estimation with Census and property price data for the same year. We present the details and results for this retrospective simulation in appendix 5.D, which shows that the model appropriately replicates changes in housing prices over time. The good fit provides confidence that the model can reasonably be used to simulate the future evolution of Cape Town's spatial structure.

## 5.5 Scenarios and prospective simulations

We consider scenarios of income growth and population trends aligned to those which inform the City's Land Use Scenarios underpinning its medium-term infrastructure master plans (City of Cape Town 2017, Medium Term Infrastructure Investment Framework). The anticipated twenty-year supply of State-subsidized housing is based on the City of Cape Town's Housing Pipeline as contained in its Integrated Human Settlement Framework (2013) (see appendix 5.F). All the other parameters remain constant.<sup>37</sup> We prospectively run simulations for the period 2011-2040.

### 5.5.1 Urban growth boundary

There has long been discussions in policy circles of Cape Town being a sprawling city. Against a backdrop where Cape Town's urban footprint was estimated to have expanded by over 1,000 hectares a year during an unprecedented housing boom during the late 1990s and early 2000s, the City introduced an Urban Growth Boundary (or 'Urban Edge') as a policy guideline and then, in 2012, as a statutory instrument. It was delineated to include sufficient developable land to accommodate future growth for at least 10 years and was thus not immediately binding. We simulate two scenarios: the 'No Urban Edge' scenario where the Urban Edge constraint is absent (and the city's urban footprint is permitted to expand unhindered into its rural hinterland) and the 'Urban Edge' scenario where it continues to be present (see Figure 5.F.1 representing the Urban Edge).<sup>38</sup>

We run the simulation until 2040, when the population of the City is projected to reach 1,770,000 households (compared to 1,068,000 in 2011).<sup>39</sup> Maps (a) and (b) of Figure

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<sup>37</sup>In our dynamic simulations, we assume that, for each income group, the wage ratios across job sub-centers remain constant over time ( $w_{gc}/w_{g'c}$  is the same for any  $g$ ,  $g'$  and  $c$ , and  $w_{gc}/w_{gc'}$  is the same for any  $g$ ,  $c$  and  $c'$ ). In levels, the mean wage for each income group grows at a constant rate.

<sup>38</sup>In South Africa, the Urban Edge enjoyed support from policymakers, academics and environmentalists alike as a means to protect valuable agricultural land, natural amenities and the functioning of ecological services, while supporting a more compact urban environment. It has been opposed by local politicians and property developers. Developers claimed that the urban growth boundary would generate regressive distributive effects since the restriction of land supply to the housing market raises the cost of housing. Politicians claimed that, by encumbering greenfield development, the growth boundary invariably stifles economic growth and job creation. The Urban Edge is not mentioned anymore in the City of Cape Town's current spatial development framework.

<sup>39</sup>The demographic growth projections used in the model correspond to the base projection used by

## 5.5. Scenarios and prospective simulations

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2 show the population density and urban footprint under the two scenarios. Without the Urban Edge, the urbanized area would expand to 1,208 square kilometers, an urban footprint that is 40% greater than if spatial growth had been contained by the Urban Edge. Densities would be significantly greater, especially in the city center. Maps (c) and (d) of Figure 2 show that the lower footprint and greater density under the Urban Edge scenario would occur with significantly higher formal prices. Within 6 km of the CBD, we find that formal prices would be 21% higher under the Urban Edge Scenario than without the Urban Edge. Because formal housing would be less affordable to the poor, there would be an increase in the demand for informal housing, as shown on the histogram (e) of Figure 2. Because we assumed no spatial expansion of informal settlement footprints (only a densification in informal settlements), these would have become saturated by 2040 and backyard housing would absorb the informality differential between the two scenarios. In the Urban Edge scenario, we find that the number of households living in informal housing would be 27% higher than in the 'No Urban Edge' scenario.

### 5.5.2 Public housing provision scenarios

Subsidized housing has been an important part of post-Apartheid policies trying to address the housing backlog. The vast majority of the approximately 336,000 households who live in public housing as of 2016 (Statistics South Africa) live in dwellings transferred as part of the RDP and later the BNG program, delivered at a rate of approximately 10,000 per year in the 1990s and early 2000s, declining to about 5,000 per year by the late-2000s due to budget constraints and diversification to *in situ* upgrading of informal settlements.<sup>40</sup>

We consider three scenarios for future public housing provision. In the first scenario (entitled 'business as usual' or BAU), we assume that the provision of public subsidized housing follows the current pace of 5,000 dwellings per year. In the 'low' scenario, we assume that construction of public housing is slowed down to a pace of 2,500 per year from 2019 onward. In the 'high' scenario, we assume that construction of public housing is accelerated to a pace of 10,000 dwellings per year starting in 2019. The sites for future public housing replicate the pipeline of projects known to the City of Cape Town starting with 'short-term projects', before considering 'long-term projects' (see map of Figure 5.F.2).<sup>41</sup>

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the Cape Town metropolitan authority as of 2019. The 1.77 million households in 2040 will correspond to a total population of 5.3 million inhabitants.

<sup>40</sup>Although government housing estates have featured in Cape Town since at least the 1920s (Wilkinson 2000), today, apartheid-era 'Council housing' only includes 43,500 rental units, 21,000 homeownership dwellings, 11,000 hostel beds and 11 old-age home complexes (City of Cape Town Integrated Human Settlements 5-year Strategic Plan 2013/2014 Review).

<sup>41</sup>The information on projects is extracted from a 2015 data set provided by the City of Cape Town, which gives the location and number of dwellings of future RDP/BNG projects, corresponding to a total of 255,000 dwellings to be built. We assume that projects indicated as 'short term' will be built before 2025, while 'long term' projects will be built from 2025 onwards.

## 5.5. Scenarios and prospective simulations

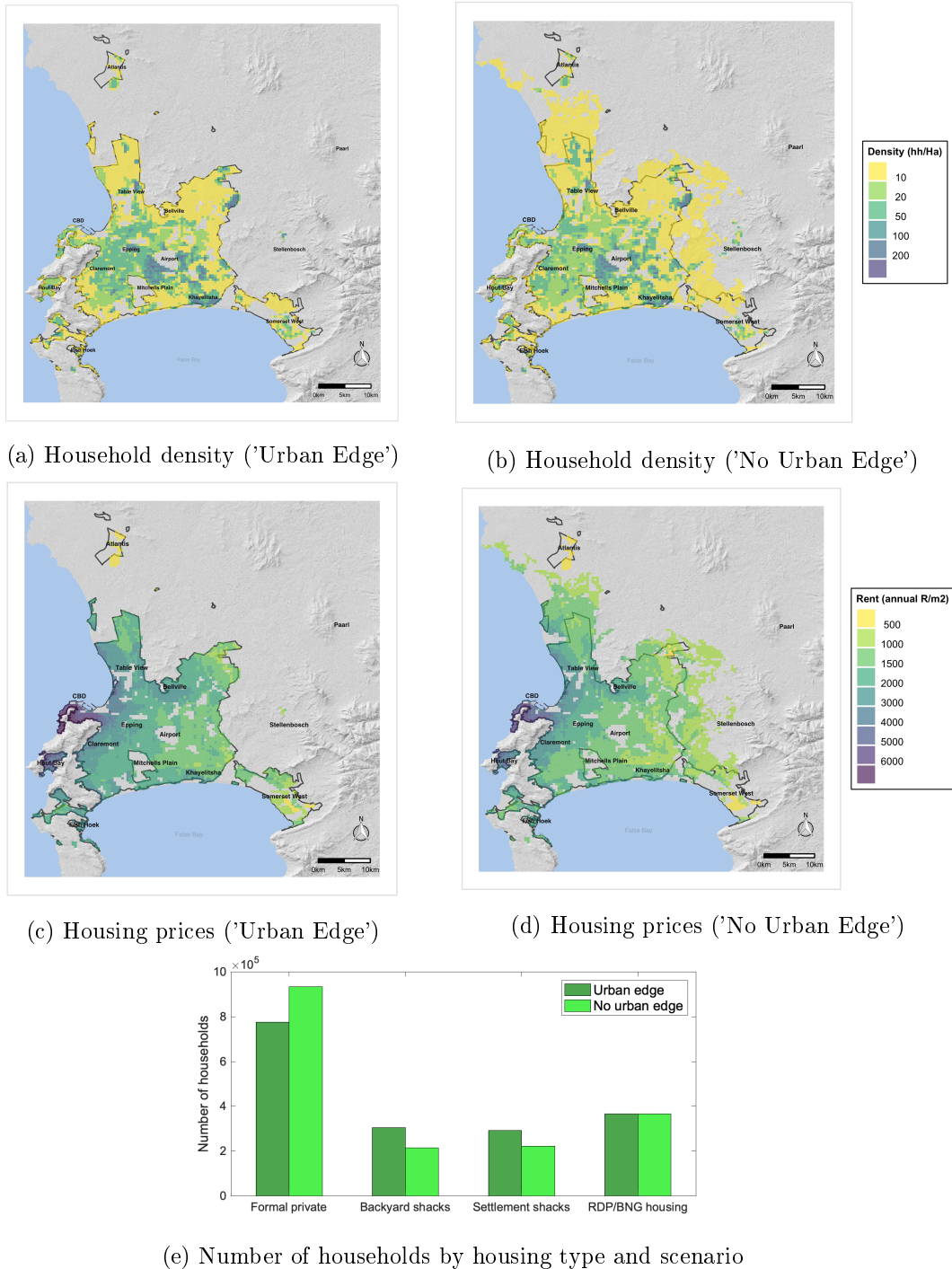
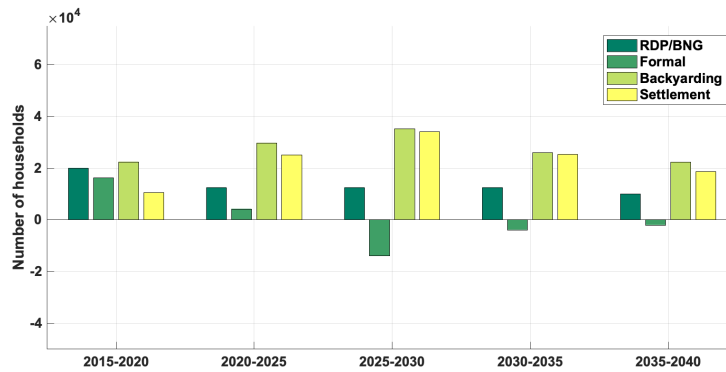
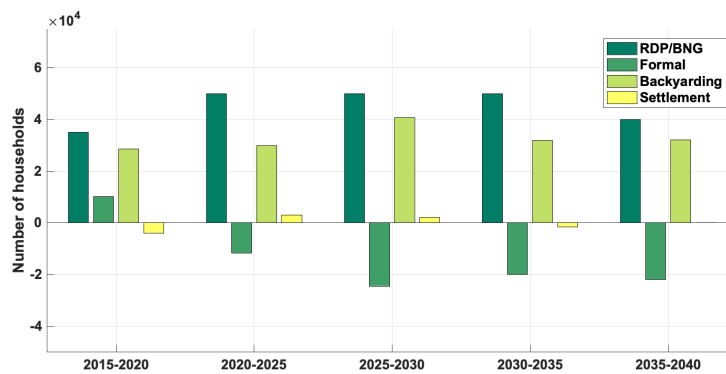


Figure 2: Simulation results for the 'Urban Edge' and 'No Urban Edge' scenarios

## 5.5. Scenarios and prospective simulations



(a) Low scenario (2,500 houses per year after 2015)



(b) High scenario (10,000 houses per year)

Figure 3: Change in the number of income group 1 and 2 households by housing type and scenario.

In Figure 3, we represent the change in the number of dwellings of each type occupied by households from income groups 1 and 2. We see that in both scenarios, the number of informal dwellers increases over time. In the high scenario, an intensification of the subsidized-housing program causes a decrease in the number of households residing in informal settlements, but the supply of backyard space induced by the construction of BNG/RDP houses results in more households in backyard housing.

### 5.6 Conclusion

The paper lays out the foundation for a simple urban simulation tool that can easily be implemented in developing country contexts and used by urban planners to generate broad urban development trends. An important contribution is the explicit modeling of both formal and informal housing markets and their interaction, which is a key feature of many cities in the developing world. Having a realistic model of that interaction makes it possible to more accurately simulate city structure in cities where informal housing accommodates a significant portion of the population (and as formal and informal housing have different land use implications). Such a model also makes it possible to simulate the evolution of informal housing over time, an important policy issue that is of course impossible to assess in a model with only formal housing. As a proof of concept, our simulations of zoning policies (with and without an urban growth boundary) and subsidized housing policies (different scenarios of the subsidized housing program) illustrate that point as demand for informal housing responds to land supply restrictions and the higher formal land prices that ensue. The increase in housing informality following an urban growth boundary is an unintended systemic effect that was not previously envisioned in the literature, which only focused on developed country contexts. As for the subsidized housing simulations, they show that income inequality and population dynamics are such that housing informality is likely to persist over time despite policy efforts to reduce it, confirming a theoretical result first derived by Cai et al. (2018). Interestingly, in the Cape Town case, the substitution of backyarding to traditional informal settlements (a trend present in the past data and confirmed in our simulations for the future) stresses the changing nature of informal housing in South African cities. This is a noticeable trend as ongoing discussions in South Africa revolve around the facilitation of such dwelling arrangements to increase access to affordable housing and to stimulate densification (see Brueckner et al., 2018, for a more in-depth discussion)

The model will be available to the wider public on an open source basis and is expected to be further refined and applied to other city contexts in the future. Specific features may be added or removed from the model depending on the context and the policy focus. Two important modifications, in particular, that we intend to prioritize for future versions of the model are the integration of endogenous transportation costs (that may change as congestion will be modified by changes in land use and transportation patterns)<sup>42</sup> and a specific modeling of public infrastructure expansion costs and their funding, an important policy challenge for expanding cities in developing countries.

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<sup>42</sup>See Larson et al. (2012) and Larson and Yezer (2015) for endogenous transportation costs in a radial version of the standard monocentric model. Introducing endogenous congestion in a polycentric simulation model such as ours would add significant complexity and is thus left for future development.



# Appendices

## 5.A Housing types and income groups

| Income group | Annual income range in 2011 (ZAR) | Average 2011 income (ZAR, estimated using Census) | Percentage of the total population in 2011 (estimated using Census) |
|--------------|-----------------------------------|---|---|
| 1            | 1 - 38,200                        | 19,580  | 38.6%   |
| 2            | 38,200 - 76,400                   | 57,300  | 16.7%   |
| 3            | 76,400 - 307,600                  | 170,140   | 28.9%   |
| 4            | > 307,600                         | 780,723   | 15.8%   |

Table 5.A.1: Income groups used in the simulation

## 5.A. Housing types and income groups

| Housing types                        | Income group(s) | Location                                    | Dwelling size (plot size for formal subsidized) | Price      |
|--------------------------------------|-----------------|---|---|------------|
| Formal private (FP)                  | 1,2,3,4         | Endogenous                                  | Endogenous, with minimum dwelling size          | Endogenous |
| Formal subsidized (FS)               | 1               | Exogenous                                   | Fixed ( $40 m^2$ )                              | Free       |
| Informal in backyard (IB)            | 1,2             | Endogenous within the backyards of FS plots | Fixed ( $20 m^2$ )                              | Endogenous |
| Informal in informal settlement (IS) | 1,2             | Exogenous settlement locations              | Fixed ( $20 m^2$ )                              | Endogenous |

Table 5.A.2: Modeling assumptions regarding housing

## 5.B. Model inputs

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### 5.B Model inputs

#### 5.B.1 Employment rates

The exogenous employment rates are the same for households within a given income group. We calibrate the parameters  $\chi_i$  as the fraction of employed workers in each income group using cross tabulations for the City of Cape Town as a whole in the Census 2011 data. For each income group, we calculate the distribution of educational attainment. We then use the distribution of employment status for each educational attainment to derive the average employment status of each income group. Table 5.B.1 summarizes the values of  $\chi_g$ .

| Income group $g$   | 1    | 2    | 3    | 4    |
|--------------------|------|------|------|------|
| Parameter $\chi_g$ | 0.57 | 0.97 | 0.96 | 0.97 |

Table 5.B.1: Values of the employment rate parameter

#### 5.B.2 Employment centers and transport costs

We extract employment center locations, their composition, and transport times to these centers from the City of Cape Town transport model, as detailed below:

**Employment centers** We use the number of jobs per income group at the Transport Zone level, estimated by the City of Cape Town in 2015 to recover local wages ( $w_{gc}$ ). For simplicity and speed of computation, we restrict the employment locations to Transport Zones with more than 2,500 jobs (185 job centers). Figure 5.B.1 shows these employment centers and relative employment size by income group.

**Transport times** We use the outputs of the City of Cape Town transport model (EMME) to retrieve the matrices  $\{\tau_{mic}\}$  and  $\{\delta_{mic}\}$ .<sup>43</sup> The outputs of EMME give us the time and distance matrices between more than 1,700 Transport Zones throughout the city, for four modes: private car, bus, train and minibus/taxi. In order to include walking as a fifth mode, we assume that individuals may also walk at a speed of 4 km/h. To retrieve the hourly wage from annual wage data, we assume that individuals work 8 hours per day, during 235 days per year. The cost of time is then valued as the time spent commuting (in hours) multiplied by the hourly wage.

**Transport monetary costs** We calculate the monetary cost of commuting by car by assuming that the depreciation cost of a vehicle is R400 per month in 2011, and that the price per additional kilometer is the average fuel price multiplied by the average fuel efficiency of cars. Past average energy efficiency of South African vehicles and the future

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<sup>43</sup>There are five OD matrices (one per transport mode) for the monetary and time costs.

## 5.B. Model inputs



Figure 5.B.1: Employment locations used in the simulation, by income group.

Note: The geographical units for the employment data are “Transport Zones”. The gray area represents the urban extent in 2012.

## 5.B. Model inputs

evolution scenario are derived from Merven et al. (2012). The Energy Department of South Africa provides historical data about fuel prices (Energy South Africa, 2016). We use the nominal retail prices (*Mogas93*). The monetary costs for public transport are derived from Roux (2013). For each mode, we assume that fares include a fixed cost and variable cost proportional to the distance. Walking has a zero monetary cost.

### 5.B.3 Land availability

Land available for formal private development  $L^{FP}$  corresponds to all land that is not constrained for construction, or occupied by subsidized housing or informal settlements. Constraints are of three types: (i) physical constraints, such as the ocean, (ii) other land-use types, e.g. commercial and industrial activities, and (iii) zoning constraints, including parks and natural protected areas.

Figure 5.B.2 maps the grid and the share of each pixel that is available for development, for each housing type ( $L^{FP}$ ,  $L^{IB}$ ,  $L^{IS}$ ).

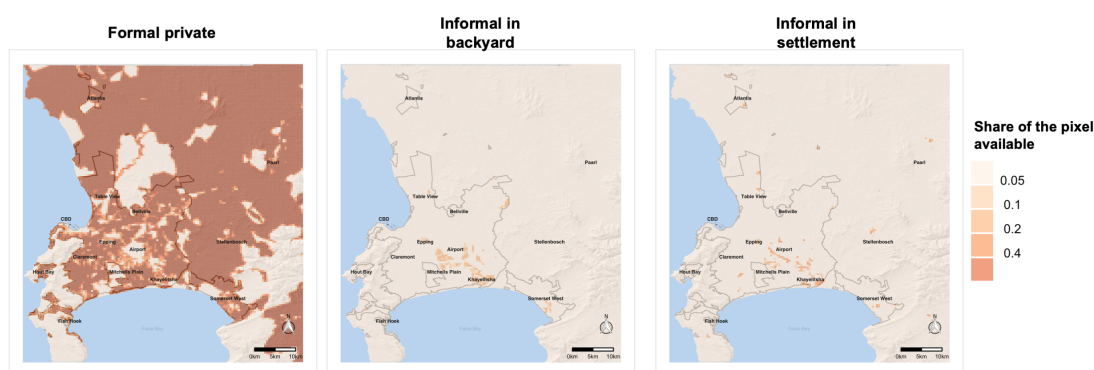


Figure 5.B.2: Share of available land for each housing type (source: 5.B.3)

### 5.B.4 Exogenous amenities

We measure amenities of different types in each location, denoted  $a_{ik}$ . Table 5.B.2 summarizes the different amenities that we include in the model, as well as the data sources. We calculate amenity values both at the Sub-Place level (for the estimation of model parameters, see the calibration section below) and at the grid pixel level (to run the simulations).<sup>44</sup>

<sup>44</sup>In South Africa, 'Sub-Places' are the equivalent of US 'Census Tracts'.

## 5.B. Model inputs

| Amenity $a_{ik}$                     | Data source   |
|--------------------------------------|---|
| Distance to the ocean                | Shoreline shapefile from City of Cape Town Open Data portal                                   |
| Distance to an Urban Heritage Site   | Sites shapefile from City of Cape Town OD portal  |
| Distance to a district park          | District parks shapefile from City of Cape Town OD portal                                     |
| Distance to a protected natural area | Shapefile of protected area layer (SAPAD Q4) from the Environment Department of South Africa. |
| Distance to a train station          | Train stations from OpenStreetMap open data   |
| Average slope                        | USGS Digital Elevation Model  |
| Presence in the Airport Noise Cone   | Shapefile from City of Cape Town OD portal  |

Table 5.B.2: List of amenities used in the model

## 5.C Calibration

### 5.C.1 Other data sets used for the calibration

We use the housing sales registry of the City of Cape Town. This data set includes records of housing transactions, including sales year, area, type, price and location of properties. We only consider transactions that took place in 2011 and aggregate the sales information at the Sub-Place level. We calculate a median price (denoted  $P_s$ ) per square meter of land for Sub-Places with more than 20 transactions recorded. We also use a data set of average formal dwelling sizes provided by the Municipality of Cape Town, at the Transport Zone level. We aggregate the values at the Sub-Place level (denoted  $q_s$ ).

### 5.C.2 Estimation of construction function parameters

We estimate the relation between the estimated stock of formal private housing and housing prices in cross-section to identify the parameters of the construction function  $\{\kappa, a\}$ . Combining equation (5.11) and the equilibrium condition (iv), we have:

$$\sum_{g=1}^4 N_{ig}^{FP} Q_i^{FP} / L_i^{FP} = \kappa^{\frac{1}{a}} \left( \frac{(1-a)R_i^{FP}}{\rho + \delta} \right)^{\frac{1-a}{a}} \quad (5.24)$$

where  $\sum_{g=1}^4 N_{ig}^{FP} = N_i^{FP}$  is the number of household living in formal dwellings. We regress the log of the previous equation at the sub-place level, denoted  $s$ :

$$\log(N_s^{FP}) = \gamma_1 + \gamma_2 \log(P_s) + \gamma_3 \log(q_s) + \gamma_4 \log(L_s^{FP}) + \varepsilon_s \quad (5.25)$$

where  $N_s^{FP}$  is the number of households in formal housing at the Sub-Place level,  $P_s$  is the median price per unit of land,  $L_s^{FP}$  is the amount of available land for formal housing and  $q_s$  is the dwelling size. From equation (5.24), we expect coefficients  $\gamma_3$  to be close to 1 and  $\gamma_4$  to be close to  $-1$ . Note that equation (5.24) theoretically only applies to formal private housing. However, because housing in low-income neighborhoods is a mix of formal private, formal subsidized housing and informal housing, we restrict our sample for the estimation, by excluding the Sub-Places in the bottom quintile of property prices  $P_s$  and for which more than 5% of dwellings are reported to live in informal housing<sup>45</sup> We also exclude rural sub-places (i.e., those that are large, with a small share than can be urbanized). We find:  $\log(N_s^{FP}) = -3.51(0.97) + 0.25(0.07) \log(P_s) - 0.98(0.07) \log(q_s) + 0.92(0.08) \log(L_s^{FP})$ , with standard errors in parenthesis. We find that coefficient  $\gamma_3$  is close to 1 and coefficient  $\gamma_4$  is close to  $-1$ . Coefficient  $\kappa$  and  $a$  in the construction function are retrieved from  $\gamma_1$  and  $\gamma_2$ , with  $a = 1 - \gamma_2$  and

$$\kappa = \frac{1}{(1-a)^{1-a}} \exp(\gamma_1). \quad (5.26)$$

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<sup>45</sup>Our data set for dwelling sizes only provides the average dwelling size at the Sub-Place level, aggregating formal and informal housing.

## 5.C. Calibration

### 5.C.3 Calibration of parameter $\lambda$ and adjusted wages $w_{ic}$

Following Ahlfeldt et al. (2015), we estimate adjusted incomes at each workplace using the population working in each job center  $c$ ,  $W_{gc}$ , the population in each residential place  $N_{ig}$ . We use aggregate statistics on the distribution of commuting distances in Cape Town to set the gravity parameter  $\lambda$ . For a given value of  $\lambda$ , we derive the vector of incomes  $y_{gc}$  by numerically solving equation (5.5), for each income group  $i$ . From equilibrium condition (v), the total number of workers sums to the total number of residents multiplied by the employment rate for each income group  $i$ . This implies that, for each  $g$ , there is a 1-dimensional vector of incomes  $\{y_{gc}\}$  that are solutions for equation (5.5). We pick the solution so that the average income of group  $g$  is the same as the average income for each income group derived from the 2011 Census. We then aggregate the total distribution of residence-workplace distances, and compare it with the data, aggregated from Cape Town's Transport Survey 2013. We select the value of  $\lambda$ , and the associated  $\{y_{gc}\}$  that minimizes the total distance between the calculated distribution of commuting distances and aggregates from the Transport Survey (see figure 5.C.1). We use  $\lambda = 4.27$ , for hourly wages.

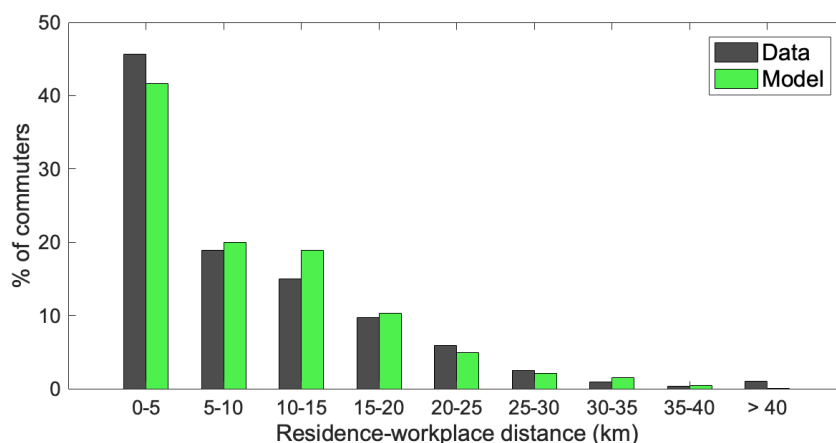


Figure 5.C.1: Residence-workplace distances from the data and the calibrated model

Source: Aggregate numbers were calculated from Cape Town's Transport Survey of 2013.

### 5.C.4 Calibration of utility-function parameters and the amenity index

We structurally estimate utility-function parameters  $\beta$  and  $q_0$ . To do this, we consider a large set of possible values for both  $\beta$ ,  $q_0$  and utilities of the four groups, and conditional on these values, we calculate the amenity index that best fits formal rent, transport and income data. We then regress the amenity index on local amenity measures available in the data. This allows us to construct a likelihood measure for the fit on amenities. In parallel, we also construct a likelihood for the fit on dwelling sizes. Among all the possible  $\beta$ ,  $q_0$  (and utility levels), we select those that provide the maximum product of



## 5.C. Calibration

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the two likelihoods. This is explained in detail below.

Using the parameters obtained in 5.C.2, we derive the rent per unit of floor area  $R_s = \frac{\rho+\delta}{\kappa(1-a)^{1-a}} (P_s)^a$ . For each Sub-Place  $s$ , we derive the dominant income group in the Census data, that we denote  $g(s)$ . We define the income in subplace as  $y_s = y_{g(s)}$ , and the related income net of commuting costs is  $\tilde{y}_s$ .

Combining equations (5.6) and (5.16) at the Sub-place level, we obtain the following relationship, for all  $s$ :

$$\frac{u_{g(s)}}{A_s} = \alpha^\alpha \beta^\beta \frac{\tilde{y}_s - q_0 R_s}{R_s^\beta} \quad (5.27)$$

where  $u_{g(s)}$  is the (constant) utility of income group  $g(s)$ , and  $A_s$  is the amenity index in  $s$ .

The relationship between rents and dwelling size is given by (5.16):

$$q_s = \beta \frac{\tilde{y}_s}{R_s} + (1 - \beta) q_0 R_s \quad (5.28)$$

We define a range of possible values for  $\beta$  and  $q_0$ , knowing that  $0 < \beta < 1$  and the minimum consumption of housing  $q_0$  must be below the size of informal dwellings  $q^{IS} = q^{IB} = 20 \text{ m}^2$ .

For each possible value of  $\beta$ ,  $q_0$ , and  $u_i$  we calculate the amenity index as:

$$A_s = \frac{u_{g(s)}}{(1 - \beta)^{1-\beta} \beta^\beta \frac{\tilde{y}_s - q_0 R_s}{R_s^\beta}}. \quad (5.29)$$

In each Sub-Place, the amenity index is an aggregate of several amenities, as given by  $A_s = \left( \prod_k (a_{sk})^{\vartheta_k} \right) \varepsilon_{A,s}$ . We estimate the equation  $\log(A_s) = \nu_0 + \sum \vartheta_k \log(a_{sk}) + \log(\varepsilon_{A,s})$  to identify the set of  $(\vartheta_k)_{q_0, \beta}$  conditional on  $q_0$  and  $\beta$ . As for the simulated dwelling sizes, they can be written as  $\hat{q}_s = \beta \frac{\tilde{y}_s}{R_s} + (1 - \beta) q_0 R_s$ . We further denote  $\varepsilon_{q,s}$  the ratio of the dwelling sizes in the data ( $q_s$ ) and of the simulated dwelling sizes ( $\hat{q}_s$ ), with  $q_s = \hat{q}_s \varepsilon_{q,s}$ . Finally, for a set of  $\{\beta, q_0, u_i\}$ , we estimate the log-likelihood that the model predicts the correct income sorting. To do that, we calculate the likelihood that the model reproduces income sorting as the likelihood of a discrete-choice logit model of land allocation to the highest bidder (consistently with competition for land within the formal private sector). Identifying the group with the highest bids as the dominant group in the data, we can write the log-likelihood for income sorting as  $I = \sum_s \left( \frac{\psi_{g(s)}(s)}{\lambda_{inc}} \right) - \sum_s \log \left( \sum_j e^{\frac{\psi_j(s)}{\lambda_{inc}}} \right)$ , where  $\lambda_{inc}$  is the scale parameter of a Gumbel maximum distribution.

We identify the coefficients  $\{\beta, q_0, \vartheta_i\}$  by maximizing the sum of log-likelihoods of the distributions  $\varepsilon_{A,s}$  and  $\varepsilon_{q,s}$  (assuming that  $\varepsilon_{A,s}$  and  $\varepsilon_{q,s}$  follow a log-normal law of mean 1) plus the log-likelihood  $I$ . We first scan a discrete set of values for the parameters. From the best solution, we then run Matlab's 'interior-point' algorithm to find the maximum. The obtained values for the parameters  $\vartheta_i$  are presented in table 5.C.1. We use these coefficients to generate a map of the amenity index for every location of the grid (see Figure 5.C.2).

## 5.C. Calibration

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Table 5.C.1: Result of the regression on amenities

|   | Residual utility (log) |
|---|------------------------|
| Proximity to a district park (< 1 km)     | -0.015 (0.02)          |
| Proximity to the ocean (< 2 km)           | 0.11*** (0.02)         |
| Proximity to the ocean (2 < . < 4 km)     | 0.08*** (0.02)         |
| Proximity to Urban Heritage Site (< 2 km) | -0.01 (0.02)           |
| Airport Noise Cone (within)               | -0.04 (0.03)           |
| Slope (between 1 and 5%)                  | 0.09*** (0.02)         |
| Slope (> 5%)                              | 0.15*** (0.02)         |
| Proximity to a biosphere reserve (< 2 km) | 0.004(0.02)            |
| Proximity to a train station (< 2 km)     | -0.013 (0.02)          |
| Constant                                  | -1.96*** (0.02)        |
| Observations                              | 307                    |
| R <sup>2</sup>                            | 0.30                   |
| Adjusted R <sup>2</sup>                   | 0.28                   |
| F Statistic                               | 14.2*** (df = 297)     |

*Note:* \*p<0.1; \*\*p<0.05; \*\*\*p<0.01

## 5.C. Calibration

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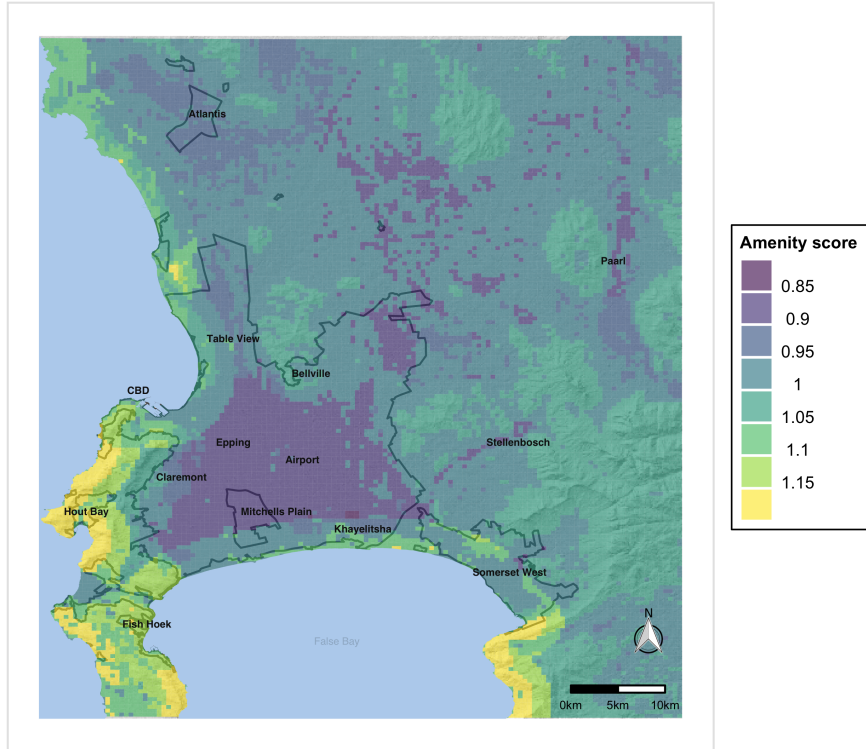


Figure 5.C.2: Amenity score

### 5.C.5 Calibration of the informal housing parameters

We run the model for a set of values for the 'disamenity' scores for living in an informal settlement or in a backyard structure ( $B^{IS}$ ,  $B^{IB}$ ).<sup>46</sup> We define a score that consists of the sum of absolute differences between the simulated and Census data shares of households living in informal settlements and informal backyard dwellings. We select the values of  $B^{IS}$  and  $B^{IB}$  that minimize this score and find  $B^{IB} = 0.74$  and  $B^{IS} = 0.70$ .

### 5.C.6 Parameter values

Tables 5.C.2 and 5.C.3 present the chosen and calibrated parameters.

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<sup>46</sup>Recall that the amenity for living in formal housing is normalized to 1.

## 5.C. Calibration

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|   |  |
|---|--|
| Maximum fraction of ground surface devoted to housing | 0.7  |
| Transport times and costs                             | cf. 5.B.2  |
| Built capital depreciation rate                       | 2.5%   |
| Cost associated with travel time                      | Equal to income per minute   |
| Dimension of an RDP/BNG house                         | Interior space $40 \text{ m}^2$<br>Backyard space $70 \text{ m}^2$ |
| Minimum dwelling size for formal private housing      | $q_{min} = 31.6 \text{ m}^2$                                       |

Table 5.C.2: Chosen parameters

|   |                                  |
|---|----------------------------------|
| Households utility function parameter                           | $\beta = 0.25$                   |
| Basic need in housing in the utility function                   | $q_0 = 4.1$                      |
| Coefficients of development function for formal private housing | $a = 0.75$ , and $\kappa = 0.04$ |
| Disamenity for living in a backyard shack                       | $B^{BY} = 0.74$                  |
| Disamenity for living in a settlement shack                     | $B^{IS} = 0.70$                  |
| Agricultural land price (in 2011)                               | $807 \text{ R}/\text{m}^2$       |

Table 5.C.3: Estimated parameters

## 5.D. Benchmark simulation

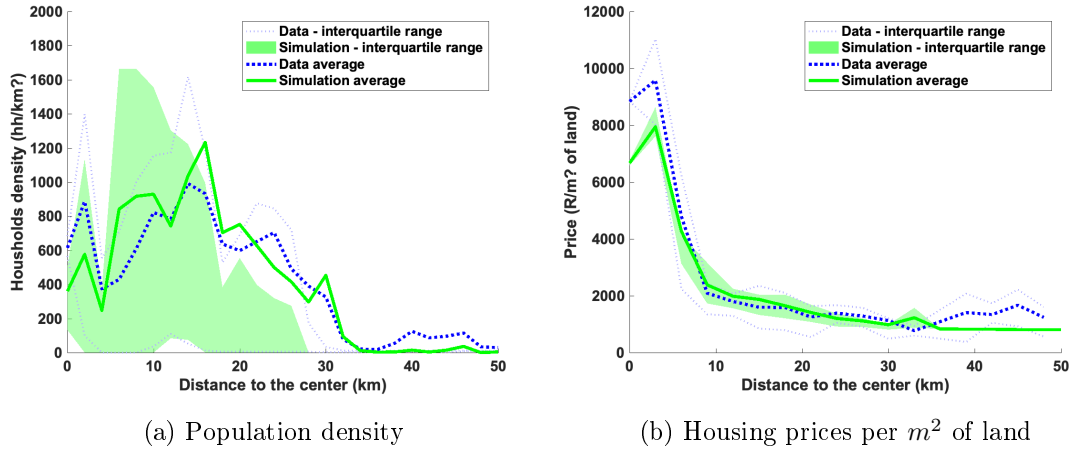


Figure 5.D.1: Comparison between simulation (green) and data (blue) for the year 2011.

Note: The dotted lines represent the average value of data at a given distance from Cape Town's Central Station.

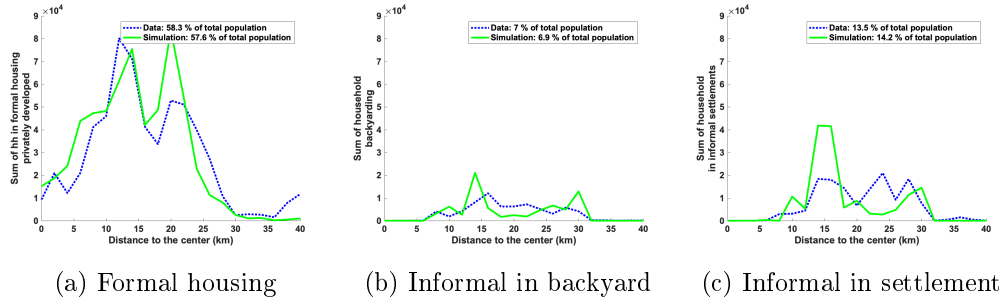


Figure 5.D.2: Allocation of households to housing types and spatial distributions: comparison between simulation and data.

Note: The figure represents the distribution of households by housing type as a function of distance from Cape Town's Central Station in 2011. Simulated values are in green, and data totals are shown in dotted lines.

## 5.D Benchmark simulation

### 5.D.1 Benchmark simulation for the calibration year (2011)

Figure 5.D.1 shows the comparison between the model's results and the data for densities and housing prices as functions of the distance to Cape Town's Central Station for the year 2011. The model captures well the main spatial trends in housing density and prices.

The model also allocates well households to the various housing types (see Figure 5.D.2).

### 5.D.2 Retrospective evolution to 2001

We run the model backwards to 2001 and compare the results of the simulation with local data (at the Sub-Place level). In this retrospective simulation, we assume that transport times remain constant, as well as the amenity index. Main inputs that vary

## 5.D. Benchmark simulation

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over time include total population, income distribution, the interest rate and the price per kilometer for fuel. Other parameters for transport costs vary proportionally to the nominal average income. Figure 5.D.3 shows the log simulated formal housing prices for Sub-Places for the years 2001, 2006 and 2011 as a function of the log median prices for the same years. Although there are local differences between simulated values and the data, the model captures the order of magnitude of prices, and their evolution over time.

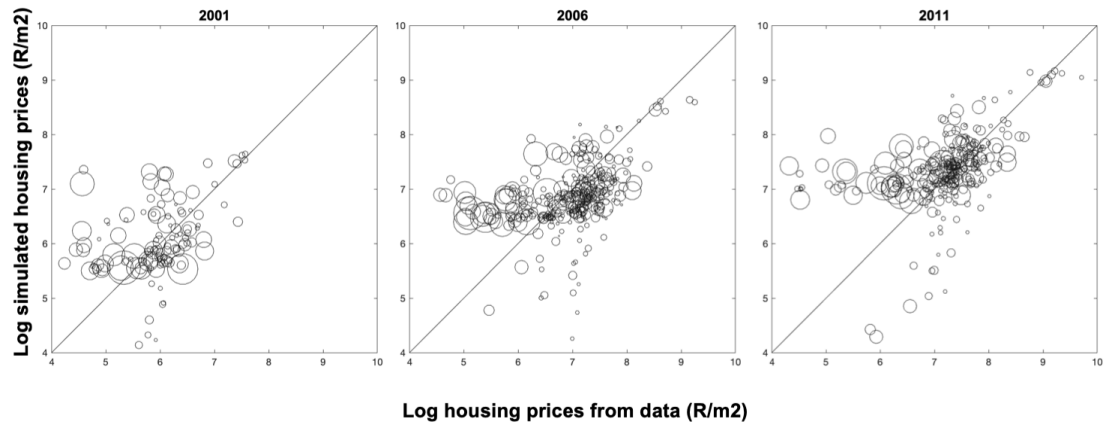


Figure 5.D.3: Comparison between log simulated formal housing prices and log median prices from the data

Note: The disk sizes are proportional to sub-place population in 2011.

## 5.E. Algorithm to solve for the equilibrium

### 5.E Algorithm to solve for the equilibrium

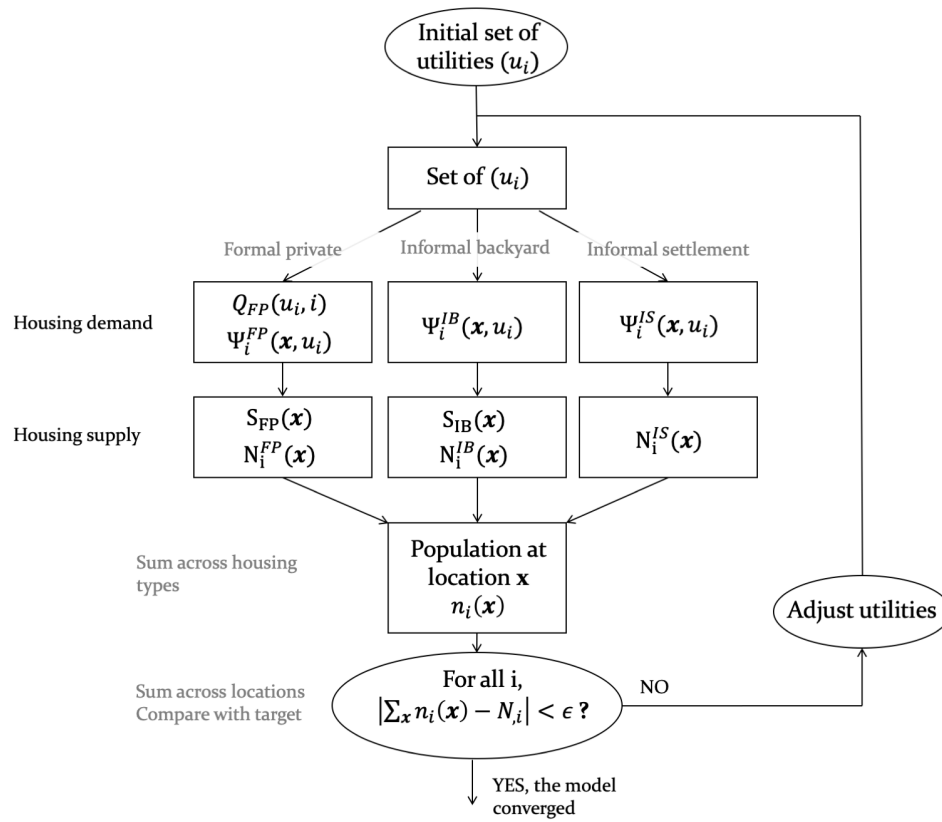


Figure 5.E.1: Solving for the equilibrium

## 5.F. Details of the reference scenario

### 5.F Details of the reference scenario

We build a reference scenario at the 2040 horizon, designed to study the effect of projected population growth on the urban structure. We assume that between 2016 and 2040, population grows at a pace of approximately 24,000 new households per year to reach 1.77 million households as projected. This corresponds to a growth of 50% over 24 years.

All other input parameters are unchanged. In particular, we assume that the relative wages between income groups, and for each income group the ratio between the wages for the different employment centers, remain constant over time. The amenity index remains constant. Transport monetary costs (for both public transport and private cars) change over time with average income. The interest rate remains constant at 3% after 2015. We assume that transport times between places of residence ( $i$ ) and employment centers ( $c$ ) do not change over time. This corresponds to a situation where future investments in transport would absorb congestion induced by population growth.

We extract the locations of future formal subsidized housing from a spatial data set of RDP and BNG projects, provided by the City of Cape Town. This data set gives the location and number of dwellings of future RDP and BNG projects, corresponding to a total of 255,000 dwellings. Moreover, it gives an indication of the project status, that we aggregate in two horizons: “Short-term” (assumed to be built before 2025) and “Long-term” (assumed to be built after 2025), as represented on Figure 5.F.2. Regarding the implementation sequence for these projects, we assume that the first properties are uniformly distributed, first across zones for “Short term” projects, then across the zones for “Long term” ones.

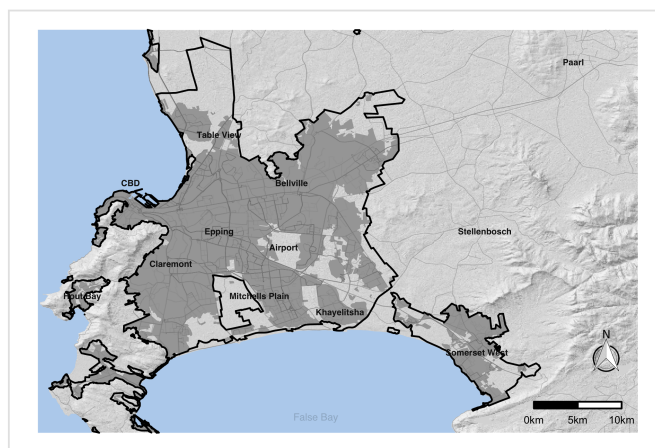
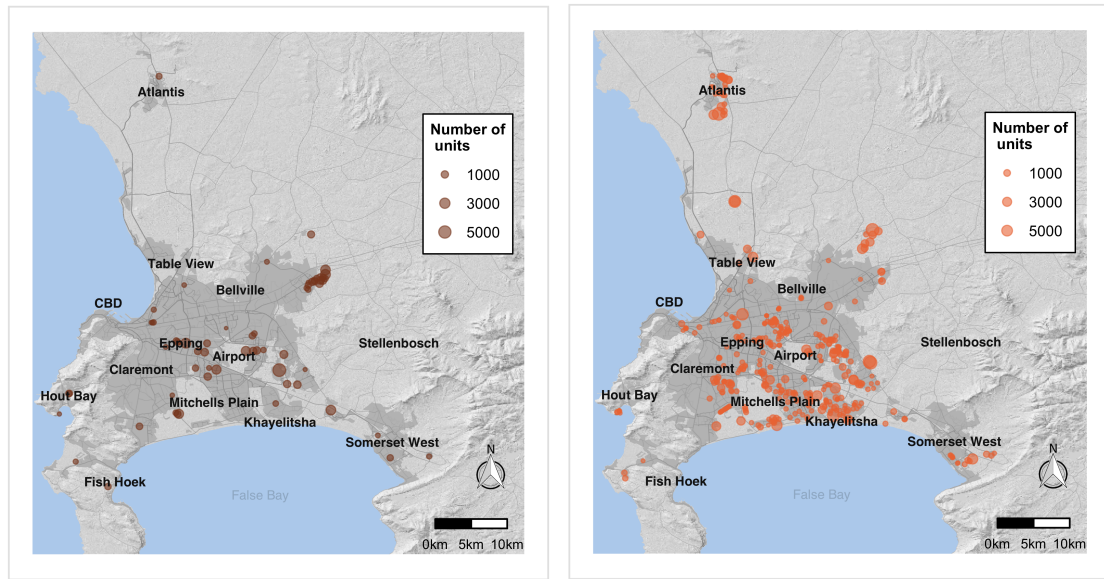


Figure 5.F.1: Urban Edge (black continuous line)

Note: The figure represents the Urban Edge as defined in the 2013 Municipal Spatial Development Framework (MSDF). The gray area represents the urban footprint in 2013. Source: City of Cape Town.



## 5.G. Summary of prospective simulations



(a) “Short-term” projects (assumed built before 2025) (b) “Long-term” projects (assumed built after 2025)

Figure 5.F.2: Pipeline of future subsidized housing projects.

Source: City of Cape Town data set.

## 5.G Summary of prospective simulations

|          |  | Baseline | Urban Edge        | Low RDP          | High RDP          |
|----------|--|----------|-------------------|------------------|-------------------|
| Scenario | Urban Edge                                   | No       | Yes               | No               | No                |
|          | RDP/year                                     | +5,000   | +5,000            | +2,500           | +10,000           |
| Results  | Urban Footprint ( $km^2$ )                   | 1,209    | 864<br>(-29%)     | 1,204<br>(0%)    | 1,205<br>(0%)     |
|          | Average housing price in the CBD ( $R/m^2$ ) | 1,508    | 1,886<br>(+25%)   | 1,513<br>(0%)    | 1,508<br>(0%)     |
|          | Households in informal housing               | 437,000  | 597,000<br>(+37%) | 465,000<br>(+6%) | 378,000<br>(-14%) |

Table 5.G.1: Summary of the outputs of prospective simulations. Percentages in parenthesis are the comparison with the baseline scenario.

# Chapter 6

## Conclusion

### 6.1 Main contributions of this thesis

If the world's future is urban, it is crucial to ensure that cities are inclusive and that agglomeration also benefits to low-income, low-skilled, populations. Agglomeration is associated with high housing costs, because of the inelastic supply of (accessible) land, long commutes and negative externalities. Existing evidence, discussed in the introduction of this dissertation (chapter 1), suggests that the costs associated with agglomeration represent a disproportionate burden on low-income residents. One of the starting point of this dissertation, following this argumentation, is the assumption that planning, housing or transport policies in cities have potentially significant distributional impacts. Chapter 3 makes a theoretical contribution in this direction, as we highlight how considering the inelastic demand for housing affects the distribution of housing and commuting costs between income groups in a city.

The distribution of housing costs, commuting costs, and exposure to local negative externalities depends critically on the within-city spatial sorting. In order to assess the distribution of costs and benefits from agglomeration and urban policies, we need to understand the mechanisms driving income sorting. Chapter 2 presents a review on this topic. Many mechanisms drive the income sorting, with no consensus on which ones are dominant. One of the challenges for theory is that real-world observations of cities' structures do not exhibit strong regularities. It is therefore complex to construct explanatory models whose scope will be general, since the conclusions of these models will conflict with local particularities. Conversely, models based on the idiosyncratic characteristics of cities (e.g. amenities in Brueckner et al., 1999) explain real-world complexity, but are also by construction more limited in providing insights about policy impacts.

In order to build quantitative model adapted for the *ex ante* assessment of urban policies, the solution may lie between general theories and idiosyncratic features. This approach is central in quantitative geographic models that gained significant interest recently (see the review in Redding and Rossi-Hansberg, 2017). The particularity of

## 6.1. Main contributions of this thesis

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these models is that the equations that (are assumed to) translate the functioning of the economy contain idiosyncratic terms, specific to each location, group, sector, and/or individual. These terms are assumed to have defined random properties, allowing both a perfect fit of the model on the data, and a clearly defined method of estimation. But, beyond the sophistication of the statistical methods, the credibility of these models depends above all on the credibility of the underlying mechanisms.

Based on this view, and given the research objective of this thesis, we spent significant attention to discussing the economic theories that explain income sorting, with the literature review in chapter 2. Noting that the urban economics literature did not convincingly address housing affordability constraints in location choices, we propose a new theoretical model in chapter 3. By applying the standard model of urban economics with a “realistic” utility function, we show that we are able to reproduce some of the broad differences between US cities, as well as changes over time, in terms of patterns of location by income.

This discussion on theory feeds the applied simulation models developed in a second part, in chapters 4 and 5.

The model of chapter 4 focuses on a specific policy —new rail transit infrastructure—and a specific mechanism —the changes in accessibility to group-specific jobs—which has received little attention so far. By focusing on this mechanism, we attempt to explain the diversity of results found by the existing empirical literature. Moreover, we simulate the effects of a future transport infrastructure “through the lens” of this mechanism. From this starting point, we can also, perhaps more importantly, discuss what is missing from the model, which we do in section 4.9. This approach is less about providing accurate predictions than about contributing to decompose the question of the distributional impacts of rail transit. The framework we built can easily be amended to add other mechanisms, including more complex representations of accessibility. As a consequence, chapter 4 “naturally” paves the way for future research.

A possible answer to the multiplicity of mechanisms is to resort to integrated modeling approaches. In chapter 5, we make a proposal to that effect, with a Land-Use and Transport Interaction (LUTI) model. The challenge is to determine what mechanisms should be included. The model was applied to the City of Cape Town as a part of a collaborative project funded by a World Bank research fund. During the project, we observed significant interest from local planning institutes for this type of applied research. When designing LUTI models, there is a tension between realism ( $\approx$  complexity) and readability ( $\approx$  simplicity). Our approach was to depart from a minimal model (NEDUM, see e.g. Viguié, 2012) and progressively integrate new mechanisms.

As a personal note, I believe that prospective models should be used with caution to inform decision-making. They rely on numerous simplifications, and foresight exercises are inherently uncertain. However, one discovery for me was the *indirect* usefulness of such exercises. The process of building a model may be of interest in itself, perhaps

## 6.2. Limits and perspectives

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more than simulation results. Since the early stage of the Cape Town project, the municipality provided valuable expertise and data. We benefited from rich discussions with local experts and planners that guided the model assumptions. While presenting early simulation results, we were able to confront theoretical economical intuitions with on-the-ground expertise about the local context. Feedback from our contacts convinced me that the exercise was also useful to them, as it helped apprehending field knowledge with a more systemic approach. Rather than *tools* to guide decision-making, simulation models may also, perhaps with more relevance, be *processes* to enable exchanges between researchers, that are able to relate to existing theories, and practitioners, with a context- and policy-relevant knowledge .

## 6.2 Limits and perspectives

In order to keep the analysis tractable, we proceeded to significant simplifications and left some important elements out of the scope of this work. We now discuss the most important elements, to our point of view, that are missing from this work, and that could represent inputs for future research. We focus on three main points: (i) the link between urban policies and the intensity of segregation, (ii) the distinction between landlords and renters, and (iii) the assumption that agents are perfectly mobile.

Simulation models must reach a certain level of empirical realism. In particular, urban economics model in which residents differ along one dimension generally result in a completely segmented city (Duranton and Puga, 2014). Such an assumption may be empirically relevant for particularly segregated cities, such as Cape Town, or for models with a very fine spatial resolution. However, European cities, such as Paris, are far from being entirely segregated. In chapters 4 and 5, we used two different approaches to introduce income mixing in the modeling framework. In practice, there is still a lot that is unknown to understand why cities are segregated, but not entirely (see e.g. Ortalo-Magné and Rady, 2008). Understanding the causes of “income sorting” versus “income mixing”, and their interaction with the spatial organization of cities, is important because, as discussed in chapter 1, segregation is often considered a problem in itself. In particular, this would be helpful to understand whether some urban policies tend to increase or decrease segregation, as for instance Bayer and McMillan (2012). Further research could also look at other dimensions of heterogeneity (e.g. households size, as treated by Fujita, 1989).

One important dimension of heterogeneity among households is the difference between renters and landlords. A key assumption of the models we used in this thesis is that all residents rent out their dwelling to absentee landlords. In practice, urban population is divided between landlords and renters. This divide is crucial to understand the distribution of benefits of urban policies. Many authors have highlighted the important political economy effects of homeownership, in particular when it comes to housing or

## 6.2. Limits and perspectives

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land use regulations (Dietz and Haurin, 2003; Ortalo-Magné and Prat, 2014). In particular, landlords gain when housing prices go up, while renters lose. Moreover, some housing policies specifically subsidize access to homeownership while others subsidize renting, and the discussion about which option should be preferred remains open (see e.g. Laferrère and Le Blanc, 2006, for a discussion in the case of French housing policies). Introducing ownership in urban models is therefore a promising direction for future research, but it represents a significant challenge, as it requires to consider the dual nature of housing: a consumption good and an investment good (Coulombel, 2010).

Another significant limitation of many urban economics model is the assumption that households are perfectly mobile. Previous analysis about urban dynamics have integrated the fact that building is a durable good (Glaeser and Gyourko, 2005; GUSDORF et al., 2008). Similarly, households do not move immediately as a response to a shock in transport prices, housing prices, or wages. “Residential immobility” is an widespread phenomenon, with significant geographical and political consequences (Lee et al., 2018). Although we mentioned “social inertia” in the introduction, we did not integrate it in the subsequent analysis and modeling exercises. However, it appears to us that relaxing the assumption of perfect mobility in spatial economic models is an important direction for future research (Rodríguez-Pose, 2018). In practice, most of urban policies leads to unequal spatial outcomes. Rail transit is a typical example of this, as it serves a limited zone where it generally increases accessibility and housing prices (see chapter 4). Urban economic models assume that, through the housing market, relocation of residents will ensure utility equalization. The relaxation of this assumption may lead to different conclusions regarding the distributional impact of such policies. In particular, it could lead to considerations about horizontal equity (whether individuals from the same group benefit equally from a given policy).

The distributional impact of urban policies appears to be at the forefront of current research about cities. An extensive assessment of the distributional effects of urban policies is an ambitious objective, which needs to be decomposed in intermediate questions. This dissertation contributed to answer some of these questions, while many remain open. I believe that the contributions and results from this dissertation represent promising early steps in a long-term research agenda.

# List of Abbreviations

**ACS** American Community Survey.

**AMM** Alonso-Muth-Mills.

**BNG** Breaking New Ground.

**BRT** Bus Rapid Transit.

**CBA** Cost-Benefit Analysis.

**CES** Constant Elasticity of Substitution.

**GPE** Grand Paris Express.

**LUTI** Land-Use and Transport Interaction.

**MSA** Metropolitan Statistical Area.

**RDP** Reconstruction and Development Plan.

**RER** Réseau Express Régional.

**SES** Socioeconomic Status.

**TOD** Transit-Oriented Development.

**UA** Urbanized Area.

**UK** United Kingdom.

**UN** United Nations.

**US** United States.

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