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Agent-based modelling of urban economic and cultural dynamics under the rent-gap hypotheses

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Summary. This work proposes a theoretically grounded, generative approach to the study of urban dynamics, based on the *Critical Geography* line of thought. We implemented a variant of the 'Rent-Gap theory of gentrification' in a set of agent-based models of varying degrees of abstraction. A stylised model of the theory - coupled with residential mobility and cultural exchange in a city-wide context - is capable of reproducing certain observed dynamics of the past century of urbanisation. Cycles of investment, the formation of persistent pockets of disinvestment, the emergence and dissolution of culturally homogeneous areas, and phenomena such as gentrification were all dynamics emerging in the simulation solely as the product of profit-driven investment in housing. A more descriptive version of the model, informed with official data derived from the UK Census and the Land Registry, provides an empirical validation of the core tenets of the theory in the context of contemporary British cities. The descriptive model is also employed to hypothesise on the mechanics and possible outcomes of large scale regeneration programmes, demonstrating a potential impact in the formulation and evaluation of urban policy. Ultimately, this work wishes to challenge the view that theory might be an unnecessary extravagance in an era of large datasets and suggestions of 'algorithmic governance.' At the same time, it wishes to highlight the actuality and insightfulness of the critical geographical approach, especially in the wake of the decidedly urban nature of the current economic crisis.

Table 0.1: Peer-reviewed papers and conference presentations that have emerged as part of the thesis and the chapter that they correspond to

Publication	Chapter(s)
Picascia, S, Edmonds, B and Heppenstall, A "Cultural diversity in gentrifying neighbourhoods" Presented at Applied Geography IGU Conference: Applied GIS and Spatial Modelling, University of Leeds, Leeds 2013	3,4
Picascia, S, Edmonds, B and Heppenstall, A "Agent Based Exploration of Urban Economic Dynamics Under the Rent-Gap Hypotheses." in Grimaldo, F and Norling, E (eds.), Multi-Agent-Based Simulation XV (213–227), Springer LNCS, 2015. DOI:10.1007/978-3-319-14627-0_15	3,4
Picascia, S "A theory driven, spatially explicit agent-based simulation to model the economic and social implications of urban regeneration" Presented at Social Simulation Conference, UABarcelona, Bellaterra 2014	3,5
Picascia, S and Yorke-Smith, N "Towards an Agent-Based Simulation of Housing in Urban Beirut." in Namazi-Rad, M Padgham, L, Perez, P, Nagel, K, Bazzan, A (eds.) Agent Based Modelling of Urban Systems (3–20), Springer LNCS, 2017 DOI:10.1007/978-3-319-51957-9_1	3,4

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Introduction

> In the centre of Fedora, that grey stone metropolis, stands a metal building with a crystal globe in every room. Looking into each globe, you see a blue city, the model of a different Fedora. These are the forms the city could have taken if, for one reason or another, it had not become what we see today. In every age someone, looking at Fedora as it was, imagined a way of making it the ideal city, but while he constructed his miniature model, Fedora was already no longer the same as before, and what had been until yesterday a possible future became only a toy in a glass globe.
>
> (Italo Calvino, Invisible cities, 1972)

Cities are complex adaptive systems.

The consensus on this assumption dates back to even before the expression itself had been devised. In the last chapter of her influential 1961 book, *The Death and Life of Great American Cities,* Jane Jacobs provides a conceptual basis for her arguments about urban form by defining cities as "problems of *organised complexity*." The core of Jacobs's view was the principled rejection of her day's strictly top-down urban renewal planning practices. Her vision of a city was that of an emergent entity stemming from the interaction of actors of different nature [52]. The intuitive conceptualisation of the city as a complex system brings with itself an equally intuitive and equally *ante-litteram* idea of the city as a system suitable to be modelled, as the Calvino quote at the top of this page seems to imply.

Within the city planning field, the notion of cities as complex adaptive systems seems to have been accepted very early, but according to Bettencourt [16], two very different lines of thought have stemmed from the common understanding of the complex nature of cities: those that view cities as systems subject to optimisation, and those that think of cities as open-ended processes, subject to gradual evolution. The first approach is directly inspired by engineering practices and more or less explicitly thinks of the city as a machine, as a set of problems to be managed and, if possible, to be re-designed altogether. This approach is the intellectual forerunner of today's *"Big Data"* strategies that, in turn, inspire the popular "*smart city*" discourse, with all its clever solutions to problems like getting to work more efficiently, detecting the optimal time to deposit the recycling, or always finding an available bicycle at the bike sharing rack.

The evolutionary view of cities, that has its intellectual forefathers in the likes of Lewis Mumford, who emphasised the historical and organic character of cities in his monumental *City in History* [63], can be thought of as the precursor of the complex systems view that insists on evolution and emergence as founding concepts, and computational models as intellectual exploration tools.

The long tradition of computational and agent-based models of urban dynamics is explored in Chapter 2. In our review we will highlight a common trait of most models, from the more abstract to the latest data driven implementations: an over reliance on a restricted set of assumptions and theories. The first of these is that *everything is bottom-up*: an assumption which seems to be, to some extent, *built-in* in the paradigm. The second is an over representation of the neoclassical economic paradigm, and an insistence on the Alonso-Von Thunen model of urban expansion. It is our persuasion that the focus on bottom-up generative modelling of urban dynamics, centred on individual or household-level agents as the main actors, has the risk of underestimating the broader economic processes that impact the urban form and constrain individual behaviour. In recent history the greatest urban transformations have been driven by large influxes of capital into urban systems: from the radical restructuring of Paris in Baron Haussman's time (1848), to the post-war suburbanisation of American cities, to the regeneration of inner cities of the last two decades. All these transformations have been driven, at least according to certain theoretical views, by the necessity of employing large amounts of otherwise improductive capital into the urban. Such transformations, in turn, have largely determined the socio-spatial phenomena that shape contemporary cities - suburban sprawl, income segregation, gentrification - without strictly originating from individual-based choices.

This takes us to the main aim of this work, which is predominantly a theoretical one. We try to model *housing* and *the housed,* integrating supra-individual, structural constraints that limit individual behaviour; avoid modelling urban dynamics as purely product of individual and household level preferences. We do so following the Critical Urban Geography approach: a line of thought originated in the 1970s, predominantly qualitative in nature. It looked at urban dynamics in terms of the social relations between the actors involved and saw the workings of the urban land market as inextricably connected to the way in which (investment) capital moves around, or *circulates*, looking for the best locations in which to be invested, or *fixed*, and to generate profit. We explore whether the critical geographical approach, that hasn't enjoyed particular consideration in computational circles, can serve as a good conceptual tool to make sense of contemporary urban dynamics. Specifically, the simulation models proposed in this work implement a variant of the Rent-Gap theory of gentrification - an approach originating in the Critical geography camp - and aim at studying whether (and how) the motility of capital may generate some commonly observed spatial dynamics, and how they relate with residential mobility patterns. We also approach some issues which, despite being crucial, did not gain great attention among modellers of the urban, specifically those affecting the city's cultural fabric in its relationship with the economic forces that shape the physical and architectural form. Specifically we will question the formation, development and sustaining of neighbourhood-level cultural identities. Our thesis is that these are interstitial and transient phenomena, resulting from cultural interactions between agents that are facilitated or disallowed by broader economic processes. Moreover, this work has the ambition of producing a tool of some practical use, possibly as a planning aide. The theoretical framework of the rent gap theory can be used to implement a conceptual representation of housing policy, centred on the economic aspect and mechanics of urban renewal. Applying such model to a real world regeneration programmes can help assessing the possible outcomes of such plans in terms of house price and social impact.

The research questions that we try to address can be summarised as follows:

- Can a model based on the assumptions of the rent-gap theory reproduce observed urban dynamics, suggesting that these may be the outcome of capital motility rather than *consumer choice*?
- To what extent can patterns of rental housing costs and occupancy be explained by movements in capital?
- How do demand-side factors in the rental housing market interact with those from the supply side?
- Can we anticipate the areas of a city more likely to attract investment for house building or restoration?
- Can we anticipate what effects on the social and cultural make up of an area a urban regeneration programme will have?

In summary, this work comprises of a computational investigation of urban dynamics at whole city scale. The study is theory-informed and data-driven. It contributes one of the first (possibly the first) comprehensive computational implementations of a theory stemming from the critical urban geography approach, and attempts a validation of its core tenets. It will couple economy with culture, try to explain transient urban cultural identities, and offer a non-mainstream perspective on the mechanics of urban regeneration.

Structure of this work

In the next chapter we review computational models of different urban dynamics: segregation, gentrification, sprawl, land use change. We will highlight (1) a general over-reliance on a purely bottom-up, individual based, vision of the nature of these phenomena; (2) the over-representation of the neoclassical economic vision, embodied in the Alonso-Von Thunen theory of land use. In Chapter 2 we also outline the 'Critical Geography' line of thought, upon which the rest of this work is based.

Chapter 3 describes our computational implementation of the principles of one of the most prominent theories stemming from the Critical Geography tradition: the Rent-Gap Theory of gentrification. We describe an abstract, highly stochastic model that implements the theory in a stylised space and is designed to demonstrate the mechanics of the capital valorization process as Neil Smith and David Harvey envisioned it. And we also outline an up-scaled version of this model, designed to run in a data rich environment, on a GIS representation of an actual urban area. Chapters 4 and 5 report on several experiments performed with the abstract and up-scaled model respectively. In Chapter 4 we demonstrate how from the simple mechanics of capital circulation, complex patterns can emerge - patterns strongly suggesting of some observed dynamics of contemporary cities, such as segregation and waves of gentrification. In Chapter 5 we attempt a validation of the model trying to reproduce the empirically observed variations in house price in the course of the last 15 years in the cities of London and Manchester. The second part of Chapter 5 is devoted to the exploration, via an extension to the model, of the social and economic outcomes of a real world urban regeneration programme.

After our conclusions and bibliography, an appendix briefly elaborates on the possible avenues that this work might take.

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Computational models of urban dynamics

> [the city is] the product of many builders who are constantly modifying the structure. There is no final result, only a continuous succession of phases. While it might be stable in general outlines for some time, it is ever changing in detail
> (Kevin Lynch, 1960 [59])

As Kevin Lynch's intuitive observation suggests urban environments can be thought of self-organising systems in permanent transition: human-made environments being constantly and endlessly shaped and re-shaped by heterogeneous agents of varying magnitude, from individuals and households to economic forces at the supra-national level, all pursuing different, often conflicting, goals. In a more systematic form, as Portugali and Benenson [76] put it - cities are self-organising systems whose parts include human individuals, who unlike atoms, plants or animals are "free agents", that is to say, they have the capacity to intend and plan their actions. Like other systems in self organisation, cities are characterised by circular causality: the behaviour of the free agent individuals participates in the process that shapes the global structure of the city and the latter simultaneously participates in shaping the behaviour of the individuals. Lynch's observation epitomises the paradigm shift between traditional urban geography introduced by the Chicago School - with its tendency to favour descriptions of static, formal models, with fixed canonic zones, sectors and nuclei - and the new quantitative geography of the 1960s and 1970s, in which geographers turned to forms of quantitative, locational analysis and spatial science in order to both identify economic laws that were common to how cities grew and changed. Some particularly fortunate theories originate in this period, and have also been popular with computational modelling: the *bid-rent theory* introduced by William Alonso in 1964 [2] focuses on economic trade-offs between accessibility and cost of a piece of land. It predicted that higher-value land uses tend to gravitate towards the centre of the city, outbidding lower rent-generating activities (e.g. housing). The bid rent theory in turn was an adaptation and formalisation of the Von Thunen theory, first developed in an agricultural context. Von Thunen's theory calculated optimal agricultural land uses based on transport costs to market, assuming a central market with given prices, given production methods + costs for any crop independent of location, and linear transport cost/distance functions.

Portugali's view, in turn, represents very well a second shift, that produced the resurgence of urban modelling in the 1990s, triggered by the advent of complexity science tools and approaches - like micromodelling and agent based simulation [86]. These approaches were better suited to examine complex adaptive systems than mathematical models which (1) allow only a limited amount of agent heterogeneity and (2) were still inspired by the traditional neoclassic economic perspective of systems tending towards equilibrium. In the past decade a sizeable literature has developed, employing complexity science tools in the exploration of the socio-spatial phenomena that shape contemporary cities - sprawl, segregation, gentrification, housing market dynamics - at different levels of detail and scope. As we will show while reviewing this corpus of study, both Lynch and Portugali's formulations, insightful as they are, also carry the mark of a bias that is quite prevalent in current computational models of urban dynamics. In avoiding the downfalls of top-down modelling, agent-based and complexity-inspired models often incur the risk of over-relying on a purely bottom-up view of systems. In the case of urban modelling this has meant centring models on individual or household-level agents as the main actors, often underestimating the broader economic processes that impact the urban form and constrain individual behaviour. While most reviews of this corpus of study tend to group the articles along the *abstract* to *data driven* continuum - reflecting the historic evolution of a field that has moved from purely stylised models towards more grounded and data-rich - we will try not to limit the view to the abstract vs data driven side of things. We will try to cover the most relevant works that examine urban dynamics using simulation techniques, we will group them according to the phenomenon that is the main object of investigation and concentrate on two other significant aspects: the focus on production / consumption and the theoretical stance, explicit or otherwise, that informs them.

2.1 Segregation - from Schelling onward

A compulsory initial mention goes to the Schelling model [80] and its numerous re-implementations and extensions. This model is probably the single most cited agent-based work, and is often considered foundational of the field. It is a highly abstract generative exploration of the phenomenon of racial segregation.

Segregation emerges, in Schelling's model, purely as a consequence of residential decisions of agents of different "colour", based on their preference towards living next to a certain proportion of similar agents. The huge significance of this model for the field seems to have triggered a sort of founder effect that drove researchers to put greater emphasis on the *consumption* side of the phenomenon, at the expenses of *production,* which has a crucial role for the emergence of segregation. The otherwise excellent review by Huang et al [50], for example, defines segregation as "an outcome of residential choices due to heterogeneity among resident types, their preferences to be near others of their type, and locational heterogeneity" (p. 3). The work of Thomas Schelling (and the very similar one of Sakoda [79], whose chessboard model might well have preceded the more famous colleague) came out in a crucial moment in economic history, when the neoclassical paradigm was gaining traction, and the "consumer sovereignty" approach was to become predominant in much economic thinking. It is not accidental that among those suspicious of this approach were the geographers. Neil Smith noted, in his seminal 1979 article [83], that

> *overemphasising consumption obscures the prime importance of the production and accumulation of surplus value which constitutes the essential dynamic of the capitalist mode of production* [...]

and that

> *restricting ourselves to this perspective, we might understand empirical residential patterns and the mechanisms according to which they are hauled through history. But we cannot understand the productive forces that do the actual hauling and that determine, in large part, the destination.*

As we will show in the course of this review, Smith's objection still applies to most computational models of urban dynamics.

The numerous extensions to the Schelling model include change to the space from a traditional grid to a Voronoi partition [9, 13, 65] or a vector layer [26]. The representation of space varies from homogeneous and featureless to heterogeneous based on more empirical conditions [92]. The two traditional types of residents (i.e. black and white) are extended to three groups, derived from an empirical survey, in Los Angeles [24], four groups in London [26], and two-level hierarchical groups (two top groups and two subgroups rather than each top group) in Tel Aviv [65]. Additionally, Ellis et. al. [34] introduced another group of households, mixed-race households, in their model. Accordingly, residents' preferences for a given group rather than other groups are not equal and can vary from group to group. In addition to the original eight neighbours, various shapes and sizes of neighbourhoods are examined [38, 56]. A hierarchical neighbourhood [67], neighbourhoods considering the barrier effect of natural elements (eg, a river) and streets [10], and a block neighbourhood, defined by the census [92], are also implemented. The migration strategies are distinguished between "satisficer" and "maximizer" [12]. The former is willing to accept any potential property with higher utility or satisfying level, while the latter only move to the location providing the highest utility or satisfying level. Besides ethnic composition, more driving forces for segregation, such as income and house quality [24], attractiveness of public goods [90], property type and agent's inertia [88].

One interesting variant to the Schelling paradigm has been the introduction of more complex cultural makeups and economic status of the residential agents. Benenson [9] represents individuals with an economic status and a cultural genotype, represented as a high-dimensional binary vector susceptible to change through interaction with its neighbours. Although the author doesn't mention it, this approach was made popular in the ABS community by Robert Axelrod's work on cultural change [3]. Benenson's model tries to provide some theoretical grounding in social psychology - here the agents experience a form of *cognitive dissonance* when surrounded by others of different cultural makeups or different economic status. As a result they modify their cultural genome or migrate to a different area. The model then studies the formation of homogeneous socio-cultural areas. Various follow-ups to this model included running it in a realistic scenario in Tel Aviv [14, 11] were subsequently developed by the author and colleagues.

Gauvin L. et al. [40] make a further step adding some market dynamics to the ethnic preference approach inspired by Schelling. The authors look at the emergence of socio-spatial segregation as a result of agent preferences for certain amenities, along with ethnic and social make-up of neighbourhoods. Prices are endogenously determined in the model by buyers' "willingness to pay" meeting sellers' "willingness to sell", the latter being affected by the intensity of the demand. A validation of the model is also attempted, with central Paris's price structure as a benchmark. Although not explicitly stated, this model falls in the crowded category of works rooted in an idealised pure-market approach, where prices are the outcome of one-to-one negotiations between buyers and sellers, or alternatively are generated via equally ideal bidding processes among interested parties. The next section has more examples of this type of works.

Jordan & Birkin [55] have a comprehensive and very sophisticated model of residential mobility which substantially extends basic Schelling-like dynamics - including variables such as price, school quality and availability of transport links as pull factors towards a location. The model features the realistic population of households - accurate regarding ethnicity, income, size - and the actual geography of a specific area of Leeds, UK. The model investigates the emergence of segregation in various scenarios, assessing the possible outcomes of a regeneration programme in such area.

2.2 Urban spatial structure, land-use change and housing markets

Among the earliest dynamics to be explored with computational modelling is the evolution of the urban form, with its regularities and discontinuities, the fascinating fundamental laws that seem to underlie certain properties of cities, like Zipf's law that links size and rank of cities in geographical systems. Michael Batty and his group have produced a number of very suggestive models that reproduced historic growth patterns of cities with abstract cellular automata based on simple local interaction of individual entities [7, 86]. Recently, in [61] they reproduced the evolution of London's street network, describing the growth patterns as fractal space-filling phenomena.

The theme of city growth and land use dynamics have also been extensively investigated with simulation models. Land use change models, and simulations of urban expansion and sprawl, in particular, tend to rely on the bid-rent theory discussed above. Some models explicitly aim at reproducing the mechanics theorised in the original work of Alonso, some others implicitly adopt the assumptions of the theory to investigate other phenomena, typically urban sprawl. In the first category falls the ALMA model, proposed in Filatova et al. [36] and Parker & Filatova [69]. This model reproduces the outcomes of the Alonso-Von Thunen theory with slightly more realistic assumptions. Centralised land price determination mechanism is replaced by a series of spatially distributed bilateral trades. The outcomes are a set of rent gradients at different distances from the centre of the city, as theorised in the bid-rent approach.

A similar work was proposed by Magliocca et al. with the CHALMS model [60]. This is a model of land-use change which reproduces transition of farmland to residential at the urban fringe. The agents are consumers, developers, and farmers, plus the land unit agent. The aim here is to reproduce classical studies (Alonso-Von Thune, again), the main assumptions are utility maximising agents and bidding mechanism for price setting.

Gaube & Remesch [39] propose a model conceived primarily as a planning aid tool. They tests alternative planning scenarios and their impact on the growth of the city of Wien, Austria. The scenarios represent different possible urban policies - favouring compact, dense new developments towards the centre of the city instead of low density expansion towards the fringe, as example. Prices are exogenous and dependent on the scenario. The authors look at the distribution of households by age group and income level across the city and the spatial patterns of energy use under each scenario.

Olner, Evans and Heppenstall [64] model the emergence of equilibrium (as in *Standard Economic Theory* equilibrium) in a housing market implemented in a stylised space representing a monocentric city with firms located in the Central Business Districts. This model is also inspired by Alonso-Von Thunen, and is based on the trade-off between accessibility and cost of land.

Urban sprawl North and South

Most simulation models of urban sprawling expansion centred in western cities seem to assume the existence of a trade-off between accessibility of workplaces and the pleasures of *bucolic* living, and to suggest that a sprawling city is ultimately the result of this tension. It is the case of Rand et al. [77] who examine urban expansion assuming exactly this kind of tradeoff between natural beauty and closeness to places of employment. Implicitly, this is Alonso-Von Thunen again. The authors examine the density of the generated settlements and the effect of different forms of the utility function (i.e. beauty/accessibility tradeoff) on density and level of sprawl. There are no prices here and no market considerations. Rui & Ban's study on sprawl in Toronto [78] also assumes the preference of people towards living "close to nature" as the main factor producing sprawl and a tension between existing residents of the urban fringe and immigrant residents. New perspective residents have a utility function to evaluate a potential living place, factoring in amenities, accessibility, etc. Existing residents can protest against new settlements, developer agents and the government are also included.

Models that examine sprawl in the context of developing countries seem to adopt a somehow similar theoretical stance, but are generally more conscious of the role of economic disparities in the evolution of the urban form. Joana Barros's models of peripherisation [5] and *slum consolidation* [6] move from the assumption that agents of varying incomes can exercise different levels of command over space, therefore the wealthier are able to settle in areas in close proximity to transport links and essential amenities, whereas those on very low or no income - often a substantial majority in the highly unequal societies of the developing world - have to find a space in the vacant peripheral areas of the city. Barros [4] examines the different growth patterns and speed of expansions that Latin American cities undergo, depending on the initial urban configuration and the extent of inequality.

Patel [70] also considers economic factors at the roots of the formation of slums. His stylised "slumulation" model includes households that make location decisions; developers that create housing units on vacant sites, pursuing profits; and politicians who subside slum dwellers, thus discounting rents, in pursuit of votes. The model looks at the density and the extent of slums under varying economic and population growth rates, employment conditions, and proportion of "prime land" upon initialisation, which are all exogenous parameters of the model.

2.3 Gentrification

Gentrification is the process by which urban neighbourhoods, usually the home of low income residents, become the focus of investment and (re)settlement of the middle classes. The term was first coined by British sociologist Ruth Glass in 1964 [41], when she observed the rehabilitation of old Victorian lodging houses in various residential areas of inner London. She argued that the return of property-owning gentry to the city was accompanied by changes in tenure and class: working class renters were being displaced by upper and upper-middle class property owners.

> One by one many of the working-class quarters of London have been invaded by the middle classes [. . .] Once this process of 'gentrification' starts in a district, it goes on rapidly until all or most of the original working class occupiers are displaced, and the whole social character of the district has changed.

Since the 1960s and 1970s, gentrification has relentlessly transformed inner city neighbourhoods and districts in places as diverse as Notting Hill in London, Harlem in New York, Society Hill in Philadelphia, and False Creek in Vancouver [81]. As Glass saw it, the city's livability, diversity and dynamism were under threat. An argument - that of gentrification depleting cities of their of diversity and cultural richness - that will hold for five decades to come, during which gentrification changed shape, becoming a different phenomenon from that observed by Glass. The gentrifiers of Glass's time channelled their labour, or *sweat equity*, into purchasing and restoring rundown and abandoned houses in former working class districts of the inner city. The somewhat romantic image of "pioneering" middle class individuals restoring older properties in working class districts no longer portraits the nature of modern gentrification in American, European, and Australian cities. As Lees and Slater [57] point out, gentrification is now increasingly the product of large scale investment on the part of sometimes supra-national investment entities, and often the State itself has a pivotal role in actively promoting gentrification, through the ubiquitous regeneration programmes, for instance. Such programmes, in the UK and the US in particular, in many cases involve the physical removal of working class housing (often, but not always, in public ownership) and its replacement with new dwellings, explicitly aimed at different demographics and social classes. City governments in neoliberal economies act less as regulators of markets to protect marginalised residents, and more as entrepreneurial agents of market processes, with an exquisitely economic agenda aimed at (1) raising tax revenues through attracting wealthier sectors of society, and (2) profiting from the sale of "prime" land to developers and speculators.

The mainstream narrative around gentrification tends to insist on the peculiar role of gentrifiers. The nature of the phenomenon has been addressed in multiple ways under different theoretical angles, but in fact with a constant predominance of consumption explanations. These insist on the postindustrial shift [8] and the emergence of a new "creative class" [37], supposedly bearing different values and tastes involving a preference towards "city living" opposed to the suburban way of life of the previous generation.

Nevertheless, the most comprehensive theory on the nature of the phenomenon is exquisitely supply-side in nature and has never lost traction since its first formulation in 1979: Neil Smith's rent-gap theory.

The rent-gap theory of gentrification and its potential applications

Neil Smith argued that gentrification is driven by the switching of investment capital from the suburbs back into the inner city [82, 83] . Capital, he showed, seeks to exploit the emergence of a rent-gap between the actual and potential value of urban property. Rent gaps tend to appear in older working class districts where capital flight has allowed properties to become run down.

Neil Smith was dealing with the continuation of the research programme started by his mentor David Harvey. Harvey had looked into the abandonment of city centres by the middle class in the 1950s and 1960s, Neil Smith started his research in the historic moment where American cities were shifting to a different stage of the valorisation/depreciation cycle, and investment capital was flowing back into inner cities. In the seminal 1978 article Smith outlines his theory of the life course of dwellings and neighbourhoods, by-products of which are gentrification and its specular phenomenon that Harvey had studied a decade before - downfiltering. Looking specifically at American cities Smith identified five stages of the life cycle of a neighbourhood leading to its decline:

1. *New construction and first cycle of use*: after a neighbourhood is built ground rent is likely to increase and house value only very slowly starts to decline. Sale price rises initially. But then "advances in the productiveness of labor", "style obsolescence", "physical wear and tear" start a depreciation cycle. Price starts to decrease.
2. *Landlordism* occurring where repairs are not promptly made and the area declines. Tenure in the area changes to rental. Undermaintenance yields surplus capital to be invested elsewhere.

3. *Blockbusting and blow out* - When the decline has reached a certain stage in an area "slum landlords" buy houses relatively cheaply and extract rent from residents that have no other choice.
4. *Redlining* - Undermaintenance gives way to more active disinvestment. Financial institutions stop granting loans and mortgaging against properties in the area.
5. *Abandonment* - The stage where the area reaches an unstoppable decline and residents start to leave.

Smith's theory of gentrification spoke back to, and also radically reworked, some of the descriptions of the Chicago School and the bid rent theorists, extending beyond the idea that this new process was simply the result of individual preferences of increasing numbers of sovereign consumers. Figure 2.1 shows the dynamic of depreciation and the profit potential it triggers, as theorised by Smith. The rent gap theory was de-

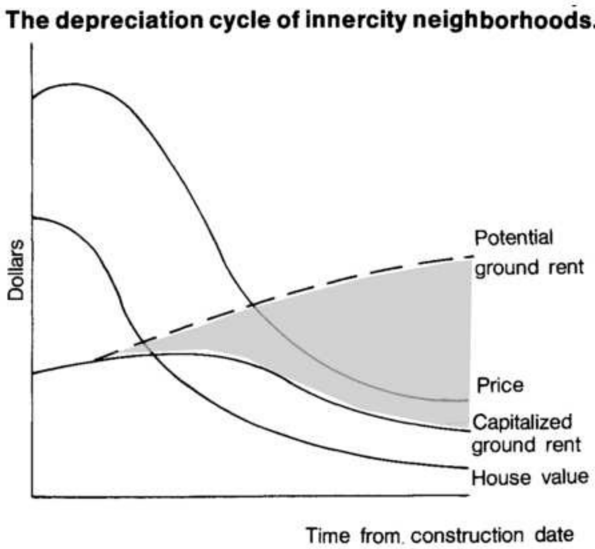


Fig. 2.1: The depreciation cycle in inner city neighbourhoods (reproduced from [84]). The rent-gap is the the grey area representing the shortfall between the actual economic return from a land parcel given its present land use (capitalised ground rent) and the potential return if it were put to its optimal, highest, and best use (potential ground rent).

bated at length in the nineties, with critics pointing out that the notion of "potential economic return under the best use" is a shading concept, difficult to quantify, and therefore - they argued - the theory's prediction capabilities are hampered [20, 19].

An unquestionable advantage of this theory, in our view, is that although it was proposed to specifically address the phenomenon of gentrification, can serve as a general conceptualisation of housing investment behaviour, suitable for a broad exploration and not incompatible with other approaches, including standard economic theory itself, as pointed out by one of the critics, Bourassa [19]. The *structuralist* line of research in human geography, a critical approach that has experienced a great revival in the wake of the housing crisis [46, 85], sees the socio-spatial phenomena that shape contemporary cities - suburban sprawl, income segregation, gentrification - as consequences of the varying influx of capital towards urban systems, as opposed to strictly originating from individual-based residential choices. This approach has hardly been explored with the tools of complexity science and simulation, possibly a consequence of the historic fracture between the traditional qualitative approach of critical geography and quantitative methods. A computational implementation of the basic assumptions of the rent-gap theory can help providing the basis for an alternative view of urban phenomena, one that steers away from the theoretical framework of neoclassical economic thinking, still overwhelmingly represented in computational urban models. This theoretical approach, with its focus on the production side of phenomena and its rejection of consumer sovereignty, can help addressing one bias of some modelling approaches, that of overestimating the purely bottom-up view of systems, as discussed at the beginning of this review.

Models of gentrification

There are relatively few models of gentrification, compared with other phenomena that have been thoroughly explored via simulation models. The very first agent-based model of gentrification was proposed by David O'Sullivan in 2002 [66]. It is a very ingenious abstract, pure cellular automation model which implements Neil Smith's rent-gap theory. The successful idea underlying this model which was adopted by other researchers is the way it implements the concept of rent-gap. In Smith's theory the rent gap is the difference between the actual capitalised rent and the potential rent that a property can achieve when put to its best use. That of 'potential rent' is a shading concept, which was criticised for its evanescence and difficulty to measure. O'Sullivan models the maximum potential rent of a property as the average (or maximum) rent achieved by neighbouring properties, so that, irrespective of the state of the property, the maximum obtainable rent is bounded by the overall state of the neighbourhood. This intuition embeds in the model the principle that the state of the surroundings strongly affects a property and builds in the model the "neighbourhood effect" that is baseline for gentrification. The initialisation procedure of this model has also been of inspiration to later research: the initial income of an household is derived from the initial physical condition of the dwelling it inhabits, which is itself derived from the "index of town centredness": a catch-all value accounting for the "desirability" of a certain dwelling. The model implements property transactions: house sales, rentals, renovations. The emergence of gentrification is measured at neighbourhood level observing the condition of properties in the area; the income of residents of the area; and the share of owner-occupiers.

Diappi & Bolchi's model [30, 31] is another explicit implementation of Smith's rent-gap stage theory. This work borrows the insight of modelling rent-gap from O'Sullivan's work – i.e. the potential expected rent is the average of the rents currently achieved in the property's neighbourhood – but adds variety in the agents definition. Agents here differentiate mainly on the basis of their knowledge. On the supply side, small landlords only have local knowledge, while big developers have knowledge over the entire market and over the broad economic conditions. The land value structure is totally dependant from the distance from city centre: the highest potential rent obtainable by a property coincides with the highest actual rent made by a property in the same-distance circle. The assumption (drawn from empirical data of Italian cities) is that land value and rent have a conical form starting from the central district of a city. The researchers observe the effects of varying levels of investment capital over the distribution of redeveloped locations.

The most detailed and feature-rich model of gentrification is due to Torrens and Nara [89]. The declared aim of this study is to enlighten the role of supply-side and demand-side factors in the emergence of gentrification. This model differs from the other gentrification models in that it doesn't build on the rent-gap theory, but still has strong assumptions about the nature of gentrification, specifically: The definition of supply side gentrification differs from the traditional Smith's approach: in Neil Smith's work the "supply" of gentrifiable properties is determined by the existence of underused dwellings (in disrepair, decaying, empty, etc.) which could be put to highest and best use with investment on the part of new residents or landlords. In this paper supply side gentrification is defined as purely new-build driven. This is an undeclared theoretical assumptions: new build gentrification differs from traditional gentrification, some argue that it is not even to be considered gentrification (see for example [29, 57], p.140). The definition of demand side gentrification coincides with immigration of higher income agents, which is implemented exogenously. This model is also the most descriptive to date and the only attempt at embedding realistic residential dynamics in a gentrification model: different areas of the district are represented, grouping individual properties in "markets"; when moving the agents select the market of interest according to their characteristics, then the property in a nested choice approach. The exogenous factors manipulated by the researcher in this model are the economic condition of immigrants and the amount of new builds, added independently in the two experimental conditions and joint in the third. The model is initialised with a realistic (ethnic + income + dwelling type) distribution of the population in three "markets" within a district of Salt Lake City. The initial economic condition of a household is inferred from the value of the dwelling it inhabits, while the ethnicity is derived from census data. The movement rules are governed by individual (household scale) weighted preferences, where all the weights are assigned randomly.

Jackson et al. [51] propose a model explicitly oriented towards demand-side explanation of gentrification. The agents considered are "professionals", "non professionals", "students" and "elderly" where professionals and students are considered potential gentrifiers and the others potential displaced. The problem of this model lies in it being extremely arbitrary in the choice and values of agent attributes. The model only considers rent and only considers the demand side. The model is coded in RePast, the space represented in the model is the actual neighbourhood imported as a raster GIS model with information on land rent and proximity to amenities. 4 agent types are included and one of the types has built-in power of increasing neighbouring land-rent.

2.4 Critical urban geography. A fertile approach in need of formalisation

As mentioned in Section 2.3 Neil Smith's rent-gap theory of gentrification is the only approach ascribable to the critical urban theory tradition to have had a tentative computational implementation. Critical urban geography is a stream of urban studies originating in the '70s with David Harvey (who supervised Neil Smith's PhD research) as its most renown representative. The focus of this research programme was to reverse the way of seeing urban problems solely in terms of their physical, anthropological, or environmental characteristics as the Chicago School did in its analyses, or in entirely abstract ideal terms, as most dominant forms of economic analysis (and the corresponding computational implementations) tend to do. It was claimed an idea of urban spaces as the product of social structures, strongly influenced by the economic paradigm. David Harvey argued that the workings of the urban land market were inextricably connected to wider social relations and to the way in which capital moves around - or *circulates*, as he put it - looking for the best locations in which to be invested - or *fixed* - and to generate profit [43]. Smith's stance on gentrification stems from this approach: there is capital *circulation* and *fixing* - in the form of large forces and structures like private property and speculation - at the origin of neighbourhood change, not individual, supposedly rational, choices and preferences ("consumer sovereignty") regarding location. That, together with the different levels of command over space that different social classes can exercise, shape the contemporary city and determine the juxtaposition of inner city poverty and decline with suburban wealth and growth, had argued David Harvey discussing the shape of cities a decade earlier, during the previous cycle, that of suburbanisation [57].

Critical geography has always been at odds with quantitative approaches, not least because formal approaches were associated with the economistic guise of the Chicago School. However, most of this body of work, the RGT in particular, is susceptible to be explored with a computational and complexity science approach. These theories stress the key characteristics of complexity - self-organisation, emergence, feedback and path dependence - that complexity science and agent-based models in particular can capture. This work employs agent-based modelling in an attempt to bridge the predominantly qualitative stance of critical geography with a more systematic and data driven exploration of some of the implications of this line of thought. In doing so, we will test its validity and shortcomings in the context of actual urban systems.

Specifically, in the tradition of agent-based modelling, we will implement in code some of the basic tenets of the rent-gap theory and try to reproduce some observed urban dynamics solely as the consequence of the forces theorised by Neil Smith operating in the urban context. The next chapter illustrates our approach.

3

The models

3.1 Introduction

This chapter[1] presents our approach in translating the assumptions of the Rent-Gap theory into an agent-based model, or rather a set of models. We started building a generic stylised model (detailed in Section 3.3), implementing the core ideas of the theory in a completely abstract space. We, then, extended the model to render it more descriptive, informing parameters with empiric data derived from the Census and Land Registry, and tailoring it on the British urban areas of Manchester and London (Section 3.4). The two models[2] respond to two different, but interrelated needs: exploring the basic processes triggered by the underlying theoretical assumptions and the patterns emerging, with the stylised model; validating the assumptions and employing the theory to hypothesise on actual urban dynamics, with the descriptive one.

Why we model

This work employs agent based modelling to pursue a number of goals. First of all we wish to explore a non-mainstream theoretical approach to urban dynamics - one that, contrary to most computational studies of the urban, integrates structural, supra-individual economic forces along with individual-level residential decisions. We do so encoding the core principles of one prominent structuralist theory, originally proposed to account for gentrification, the Rent-Gap theory (RGT) - introduced in the previous section. The RGT explicitly acknowledges the predominant influence of structural economic factors in the production of urban dynamics and focuses on the *supply side* of the housing market. We believe that

[1] Parts of this chapter are based on [72]

[2] Both models and accompanying material are available under a free software license on the author's GitHub repository https://github.com/harrykipper/gentaxelling

its insights can be generalised to explore other dynamics not explicitly included in the original formulation, and an agent based model can be a formidable tool for such theoretical exploration and generalisation [32]. One of the purposes of modelling, after all, is to suggest analogies between seemingly unrelated processes, as Epstein [35] pointed out in his taxonomy of the numerous *reasons to model*.

We'll try a first step towards this endeavour by testing the ability of an abstract implementation of the rent gap theory to reproduce *in silico* some of the dynamics observed in contemporary cities - even if not immediately related to the original formulation of the theory - highlighting the structural factors that may be contributing to their emergence, and clarifying the core dynamics that may generate such phenomena. This is not the sole purpose of this work though. Agent based modelling can also provide something that the rent-gap theory has been lacking for many years: *validation*. Despite some attempts at identifying rent and value gaps in cities across the US and Australia during the 90s [20], the rent-gap theory has never undergone a systematic validation. This was due to the difficulty of gathering significant data at the time, and the long time span that an accurate empirical evaluation of the outcomes would have needed. One of the primary strengths of ABM is, in fact, as a testing ground for a variety of theoretical assumptions and concepts about human behaviour within the safe environment of a computer simulation. Applying an agent-based model of the theory to an empirical, data rich context, and trying to reproduce observed historic patterns will provide first step towards a much needed validation for a theory rooted in qualitative speculation that, despite its elegance, has often encountered criticism for being ill-specified and of scarce predictive value (see for example [19]). The RGT is an approach worth rediscovering and updating, especially in the light of the decidedly urban nature of the recent economic crisis. This theory shares its core principles and assumptions with a large body of predominantly qualitative work in human geography - the critical, structuralist approach discussed in the previous section - that, however interesting and potentially powerful as interpretation tool, has never had systematic empirical validation attempts. A computational implementation can provide a step towards its acceptance.

Building a comprehensive model that captures the tenets of the critical geographical approach would entail accounting for what David Harvey terms the *peculiar necessities of circulation of capital through the built environment*. An accurate descriptive model would include all the roles of the economic agents involved: *landowners* who receive rent, *developers* who receive increments in rent on the basis of improvements, *builders* who earn profit of enterprise, *financiers* who provide money capital in return for interest, and finally *the state* who can use taxes as backing for investments which capital cannot or will not undertake, but which nevertheless expand the basis for local circulation of capital [44].

The model proposed here does not include the entire set of actors envisioned by Harvey. The present model sacrifices some detail on the supply side to extend the scope of the analysis and include the demand side of the urban economy. Our approach is to capture and test the *principles* of the theory, which are focused on the supply or production side, and explore them in relation with the other end of the equation: individuals‘ and households‘ residential mobility. The fundamental insight of the RGT (and of the critical urban geography tradition at large) that we encode and base our modelling exercise upon is that the economic forces operating in an urban context can be described as “*capital*” - defined as the aggregate monetary amount invested in restoring, building and upgrading properties in a city - and the main propellant for its motility is the pursuit of profit, from property sale or rent extraction. Our primary purpose is to explore the dynamics of capital circulation and its effects over the social and cultural fabric of the city. Our main focus is, therefore, the intra-urban level.

In the next paragraphs we detail the rationale, the methods, scope and purposes of the analysis, the design principles of the model, the validation approach. In the subsequent chapters we discuss the results, the validation and then progress to employing the framework to develop hypotheses over the possible outcomes of a real world regeneration programme ongoing in Salford, UK.

3.2 Rent-gap. From theory to model

The core of this work comprises of two agent based models, implemented on the NetLogo platform [91], that encode the tenets of the rent gap theory in two different types of space and under two different sets of assumptions. The first is an abstract, stylised model where agents operate in a regular grid of locations under a highly stochastic parameter space; the second is, essentially, the same model, running in a more realistic space, with parameters based on data as empiric and official as possible.

John Casti [22] has drawn a fundamental distinction between *abstract* and *realistic* models, which relies on the analogy of the difference between a photographic portrait and a Picasso portrait: one attempts to mimic reality; the other, while capturing parts of reality, focuses on particular aspects in the hopes of emphasising fundamental features. Abstract and descriptive modelling sit on the opposite ends of a continuum that is temporal and methodological. At one end, purely theoretical and stylised models have been developed in geography to simulate classical urban residential problems, such as monocentric patterns of cities and segregation of residents [15, 28]; at the other end, empirical models driven by extensive spatial and non-spatial data are constructed to simulate residential choices within a complex urban system [17, 93]. Between the two extremes, a number of models, which are based partly on empirical situations and partly on theoretical findings, are built to simulate urban residential phenomena, such as gentrification and urban sprawl [50]. With our twofold implementation we cover two points of the spectrum: one is a simple, abstract model, the other more complicated, aspiring to a higher degree of realism.

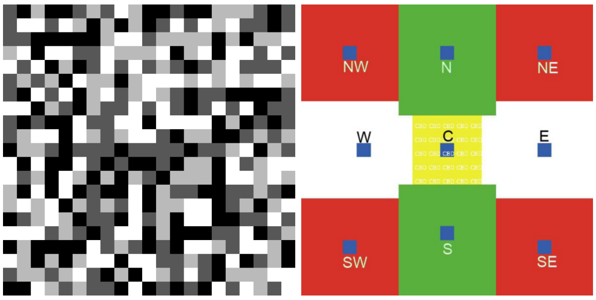
In the *abstract* model, described in 3.3, we implement a process, and explore the basic, emerging, patterns that it produces. Specifically, we explore the basic implications of a simple assumption on the nature of investment and on the life course of buildings by implementing it in a stylised space, along with stylised residential mobility implementing the demand side of an housing market. We explore their joint impact on the characteristics of a city - specifically its economic, social and cultural configuration; we then discuss some emerging patterns: the production of geographically uneven economic development, the emergence and dissolution of culturally peculiar areas within a city, the emergence of phenomena typical of urbanisation, like gentrification, segregation and sprawl.

With the "*realistic*" model (3.4), we aim at different goals: one being validation, and the other a "what-if", or scenario analysis of a real world regeneration programme. We try and validate the premises of the theory, as encoded in the abstract model, in two realistic urban contexts: Manchester and London. We initialise the model with parameters drawn from the 2001 census, and try to validate the outcomes of the model comparing the results with the 2011 census. A variant of the model is then employed to generate hypotheses on the possible outcomes of a specific regeneration programme in an area of Salford, Greater Manchester.

3.3 The abstract *gentaxelling* model. Basic specification and core dynamics

The model represents a city composed of three layers: (a) the city's infrastructure; (b) human agents that move throughout it, interact and influence each other; (c) economic forces that impact on both components, in the form of capital seeking to profit from housing renovation. The objective of the abstract leg of the modelling exercise is to investigate two aspects of the relationship between the three components: (1) the economic and spatial dynamics emerging from the interaction between investment / disinvestment cycles and residential mobility patterns; (2) the impact of such dynamics on the city's cultural fabric - specifically the conditions of emergence and dissolution of pockets of culturally peculiar areas within a city. The entities represented in the model are: (a) individual locations (residential properties), defined by their value and repair state; (b) individual agents that represent households, characterised by an income, mobility propensity and cultural configuration; (c) economic forces, represented in the form of exogenous "capital" level, aiming at profiting from redevelopment/restoration of residential locations. Each of the three aspects is described in detail in the following subsections.

3.3.1 City structure and economic dynamics



(a) (b)

Fig. 3.1: The city is composed of 441 residential locations, each with a maintenance level and an economic value, divided in nine neighbourhoods. The colour shade of locations represents maintenance state from white (best condition) to black (worst). Depicted in (a) is the typical model initialization with random values assigned. The nine neighbourhoods (C, N, NW, NE, E, W, S, SE, SW) have a local centre (b). The district boundaries are "soft", they do not constrain the agents' behaviour.

We represent a city as a 21x21 square grid of 441 residential locations (Figure 3.1a) characterised by a value V and a maintenance level, or repair state, r, grouped in 9 districts (Figure 3.1b). An initial population of agents occupying 65% of the available residential locations is generated at initialisation (see Section 3.3.2).r is initially set at random in the 0-1 range and V is set at $V = r + 0.15$. Dwellings progressively decay in their condition by a factor $d = 0.0012$ assuming that, if unmaintained, a location goes from 1 to 0 (becomes inhabitable) in 70 years (1 simulation step = 1 month). In order to match the theoretical assumption of a decline in property price over time, we set the value of the dwelling as decreasing by a depreciation factor of 0.02 / year. We also assume that in case of prolonged emptiness of the dwelling (>6 steps) both decay and depreciation factors are increased by 20%. The model represents investment in housing renovation/redevelopment as the fundamental economic force operating in the city. This is implemented by the "Capital" parameter, K, which represents the maximum number of locations that can be redeveloped in the current economic climate, expressed as a fraction of the total number of residential locations of the city, similarly to the approach proposed in [30]. A value of $K = 0.02$, as an example, means that every 12 steps $441 * 0.02 = 8$ locations in the city receive investment. Consequently a high level of K represents a large inflow of investment in the housing market, which may result in more locations being redeveloped and gaining value. The selection of the locations where the investment lands is carried out deterministically, based on the value-gap of a location with the neighbouring properties, in accordance with the RGT.

'Highest and best use'

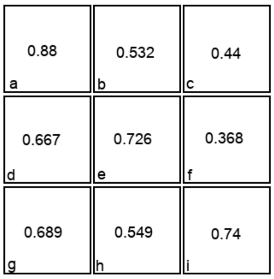


Fig. 3.2: Example of price gap formation. The numbers represent locations' value

One of the main sources of criticism towards the RGT was the abstract formulation of "highest and best use": the unspecified maximum return that a plot of land is capable of achieving. In this model we determine the value gaps in accordance with the *neighbourhood effect*, the principle that the amount of rent or the sale price attainable by a given location is always bounded by the characteristics and desirability of the area where the property is located. A principle effectively summarised by the *"location! location! location!"* mantra of estate agents, strongly reminescent of Waldo Tobler's first law of geography that *everything is related to everything else, but near things are more related than distant things [87].*

In this implementation, we assume an upper boundary to the value of a property after redevelopment: the average, or maximum, value of neighbouring properties. Still, there is more than one way of implementing this principle and we tested four different approaches, all in accordance with the principle of neighbourhood effect. As detailed in the next chapter, these give rise to somewhat different outcomes.

- *Mean*: This approach mimics the policy of many cities around the world (i.e. Berlin) that seek to limit excessive rent increases. After renovation or redevelopment a property's price is brought to the average of the neighbourhood plus a 15% premium for renovation. (Equation 3.1)
- *Max*: Variation of the mean method: Price is brought to the maximum of the area, plus a small increase over such maximum.3.2
- *New*: This is a mix of the two above: maximum of the immediate neighbourhood of the dwelling being restored (*Moore* neighbourhood - the

eight locations immediately surrounding), or mean of the whole district, whichever the *highest*.

- *Lnd*: This method is slightly more sophisticated and introduces some demand-side considerations. Here, after renovation, the new price of a dwelling is the mean of the inhabited locations in the immediate proximity (radius 2 patches - these may also include locations that fall in a different district, eq.3.3). If no locations in such radius are inhabited the mean price of the neighbourhood is considered reduced of 25%, then the renovation premium is applied. The rationale is that if an area is not attracting residents the "asking price" will reflect it in some form.

More formally, we set the new value nV of a redeveloped property p at the neighbourhood average, plus 15% (representing a premium for a newly restored property) as in equation 3.1, or at the neighbourhood maximum (equation 3.2). As an example, the price-gap for location *e* in Figure 3.2, is 0 if Eq. 3.1 is used ($1.15 * [(0.88 + 0.532 + 0.44 + 0.667 + 0.368 + 0.74 + 0.549 + 0.689)/8] < 0.726$), and 0.154 ($0.88 - 0.726 = 0.154$) if computed with Equation 3.2 (assuming that we are considering the Moore neighbourhood - the eight locations surrounding the central location *e* - instead of the whole district for comparison). Therefore, the method based on local maximum will generate a higher number of locations with a positive price-gap, that based on the average will have less, generating, as we will see, more concentration. In order to model the possible varieties of neighbourhood effect, we also consider a vicinity to be either the Moore neighbourhood of a location or the entire district that the location falls in, *whichever is bearing the highest values* and therefore grants the highest return for an investment. The four mechanisms described above can be formalised as follows

$$nV_p = 1.15 * max\,(avg(V_{moore}), avg(V_{district})) \tag{3.1}$$

$$nV_p = 1.15 * max\,(max(V_{moore}), max(V_{district})) \tag{3.2}$$

$$nV_p = 1.15 * avg(V_{radius2}) \tag{3.3}$$

The value gap for location p will be $G_p = nV_p - (V_p + C)$, or 0 if $G_p < 0$. Here C is the cost of removing the present resident if the location is occupied. Once a location is selected for investment its value is set at nV_p and its repair state is set at $r = 0.95$. In the case of Eq. 3.3 if no locations surrounding p are inhabited, then V_{radius2} is reduced by 35%, as the third mechanism tries to mitigate the strong supply-side focus of the RGT by embedding a demand-side consideration in the price formation mechanism. Table 3.1 summarises the variables associated with location.

Table 3.1: Location variables

Name	Type/Range	Description
r	float, {0,1}	Maintenance/repair state
V	float, {0,1}	Value
G	float, {0,1}	Value-gap: difference with neighbourhood value
d	integer	Euclidean distance from the centre of town
te	integer	Time empty
o	boolean	Occupied?

3.3.2 Agent model: cultural exchange and residential mobility

Agents in the model represent individuals or households. They are endowed with an income level, i a mobility propensity m and a numeric string that represents their cultural configuration (Table 3.2). The agent's income level is set at random, normalised to the interval $\{0, 1\}$ and represents the highest price that the agent is able to pay for the right of residing in a property. The model, ultimately, implements a pure rental market. The agent's culture is modelled as a n-dimensional multi-value

Table 3.2: Agent variables

Name	Type/Range	Description
m	float, {0,1}	mobility propensity
c	list t=10,v=4	culture: memetic code
i	float, {0,1}	Income level
d	float, {0,1}	Cognitive dissonance level
th	integer	Time here: steps spent in the current location

string of *traits*, inspired by Robert Axelrod's classic agent-based model of cultural interaction described in [3] and originally applied to the urban context by Benenson in [9]. The string represents an individual's *memetic code*, or "cultural code": an array of t cultural traits, each of which can assume v variations, giving rise to v^t possible individual combinations. In our model each trait is susceptible to change under the influence of other agents. Cultural influence is localised: agents that have been neighbours for more than 6 consecutive steps are likely to interact and exchange traits, thus rendering the respective cultural strings more similar. Following Axelrod, we assume that the likelihood of cultural exchange is proportional to the similarity of two neighbours' cultural array. At each time step agents compute the similarity of their memetic code with one randomly picked neighbour's. The similarity between two agents is the proportion of traits that they share, computed with Equation 3.4. One random member of each couple of agents with $sim > 0.3$ will replace one of the dissimilar traits with a trait picked from the partner's array.

At the same time a cultural *cognitive dissonance* effect is at work, implementing a concept proposed by Portugali [74, 75] under the label of *spatial cognitive dissonance*: this is, roughly, the frustration of being surrounded by too many culturally distant agents.

$$sim_{ab} = \frac{\sum_{i=1}^{t} xor(index(i, agent_a), index(i, agent_b))}{t} \tag{3.4}$$

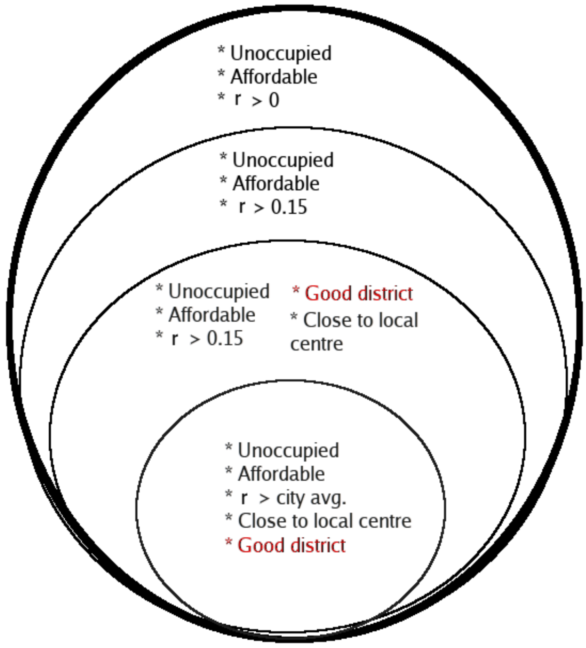


Fig. 3.3: The residential choice process. A dwelling has to be affordable, free and habitable ($r > 0$) for an agent to consider moving into it. If these requirements are met, other characteristics are considered. If any district has developed an allure, agents who are relocating consider whether it suits them, based on a homophily preference. When no dwelling meets the outmost requirements the agent leaves the city.

Agents who spend more than six months surrounded by neighbours with few common traits ($sim < 0.3$) increase their mobility propensity each subsequent time step. The mobility propensity attribute represents the probability that an agent will abandon the currently occupied location in the subsequent time step. This parameter is set at a low level in the beginning of the simulation, drawn from a Poisson distribution centred at $m = 0.0016$, meaning that, on average, agents have a 2% chance of moving each year. Mobility propensity is affected by the conditions of the currently occupied dwelling and the aforementioned cognitive dissonance level. One agent's m is increased as follows: $m_{t+1} = 1.5m_t$ in the following circumstances:

- After 6 months in a dwelling with $r < 0.15$ (excessive time is spent in a dwelling in excessively bad condition)
- the cultural dissonance level exceeds a threshold for a period of 6 continuous steps.

A special circumstance is when the price of the dwelling currently occupied exceeds the agent's income. In such case the agent is automatically put in "*seek new place*" mode. This represents an excessive rent increase, unsustainable by the agent. The process of finding a new location is bounded by the agent's income: a new dwelling has to be affordable ($V \leq i$), in relatively good condition, and as close as possible to the centre of the district which contains it. The selection process is represented in Figure 3.3. If no affordable and free location is to be found, the agent is forced to leave the city. As Figure 3.3 shows, in certain cases the residential choice process of an agent includes the cultural configuration of the district as a factor.

A special district-level variable called *allure* is set when the degree of cultural uniformity within a district exceeds a threshold, thus making the area recognisable for some of the features of its inhabitants. We measure cultural uniformity, u, as the average distance between the x agents residing in a certain neighbourhood.

$$pairs = \frac{x(x-1)}{2}$$

$$u = \frac{\sum_{i=1}^{x} \sum_{j=1}^{x-1} sim(agent_i, agent_j)}{t * pairs}$$

The allure of a district is represented as a string of cultural features, similar to that of individuals, where each element of the string is the most common value for that trait in the district population. A district's allure is therefore an emergent feature of the model, which may or may not appear. This reflects the fact that not every neighbourhood has a special connotation visible to agents, but only those with a recognisable population do.

Table 3.3: District-level variables

Name	Type/range	Description
u	float,{0,1}	Cultural uniformity
a	list	Allure (cultural makeup)

The allure attribute can be thought of as the *reputation* of a neighbourhood in the eyes of agents. The attribute is sticky, after its emergence it is updated seldom and doesn't necessarily reflect the current composition of a district, representing the fact that reputation is a nearly permanent feature, difficult to eradicate or to replace [25], a characteristic that applies to places‘ as well as humans‘ reputation. Once a district's allure has emerged, the district becomes recognisable to agents, who will take the allure into account in their residential decision under a homophily constraint: the agent will seek to move to a district with an allure similar to her culture string.

Table 3.4 below reviews the main functions run at every simulated time step.

3.3.3 Limitations of the abstract model

There is one large conceptual elephant lying in the *model room*: the distinction between *value*, *ground rent*, and *sale price* in Marxian theory. The aim of the abstract model is to implement a computational version of the Rent Gap Theory, a theory that funds its assumptions on the Marxian theory of rent. One grand simplification operates in our version, with regards to the original source of inspiration: we identify ground rent with sale price (or monetary rent). While there is an obvious relationship between the two, the concepts are by no means interchangeable. Rent and sale prices are a function of ground rent, but other factors intervene in the formation of prices. This is apparent in Picture 2.1, where Price, House value and Ground Rent are represented.

Apart from this theoretical non-congruence which, in the context of a modelling exercise, can be tolerated as an “abstraction artefact” of sorts, a second ambiguity exists: all locations in the city are treated as rental. In other words, the model currently lacks an implementation of *tenure* (but see Appendix 7.2). This has consequences in the dynamics of the model in that some phenomena (i.e. gentrification) are obviously altered: in a situation where prices rise, for example, all agents with an income lesser than their current house price have to move out - as a price increase equates to a rent increase. However, the same situation in a more realistic setting, with different tenures implemented, would see only a subset of agents forced to leave: owner-occupiers, for instance, would have a choice

Step function

`while K > 0 {`
`find location with max price-gap;`
`redevelop location;`
`location.price = average(neighbourhood.price) + premium`
`location.condition = 0.95`
`K = K - 1}`

`exchange-traits;`
`update dissonance-level;`
`if (dissonance-level > threshold) or (price-here > myincome)`
`   identify pleasant-neighbourhood;`
`   if any empty location with [`
`    neighbourhood = pleasant-neighbourhood and`
`    price < myincome]; then`
`     move-to location`
`   else`
`     move-to empty location with price < myincome`
`   else`
`     leave-city`

`update prices;`
`update repair-state;`
`update price-gaps;`

Table 3.4: Abstract model step function: supply side (top); demand side (all resident agents, middle); environment (bottom)

to stay, or rent out, or sell the property. The net effect, in this case, is an acceleration of gentrification and an alteration of the social and cultural makeup of the area faster and more profound that would be. It might be argued that, in the context of a stylised model, such inconsistency does not necessarily hamper the relevance of the outcomes. On the contrary, having the dynamics unfold faster and in a more clearly cut fashion, can be helpful in making processes more visible.

3.4 Linking GIS and agent-based model: testing the theory in a realistic space

Scaling up the model from a simple, regular grid geography to a closer representation of an actual urban area involved coupling agent-based modelling with tools from geography, such as Geographical Information Systems.

The coupling and embedding of Geographical Information systems and agent based modelling is a recent and very welcome addition to the spatial complexity science toolbox [27]. For agent-based modellers this integration provides the ability to have agents that are related to actual geographic locations and their features. This is obviously of crucial importance when modelling urban systems, as everything is connected to the notion of place. For GIS users, it provides the ability to model the emergence of phenomena through individual interactions of features within a GIS over time and space. In Geographical Information Systems the world is represented as a series of layers (such as the physical environment, the urban environment) and objects of different types, which can form the artificial world for the agents to inhabit; they can act as boundaries for our simulations, or fixed layers such as roads provide a means for agents to move from A to B, or houses provide them with a place to live.

In our case, we used GIS to superimpose multiple data layers to the abstract model detailed above, and populate all the location and agent-related variables - stochastic in the abstract model - with their actual value in a given area of the city. GIS also allowed us to run the model on the visual representation of an actual urban area: we were able to construct GIS models of Manchester and London - embedding vector data on geographical boundaries (postcode and census areas at different detail levels), house prices, household income, ethnicity and religion of the inhabitants - employing data gathered from the various sources indicated in Table 3.5 and 3.6 and detailed below. The GIS models were then imported in NetLogo via the GIS extension, generating the configurations shown in figures 3.4 and 3.5.

In the case of Manchester, the modelled city is composed of 5,583 locations, the London model has 10,888, all of which assumed to be residential, endowed - as in the abstract model - with a maintenance state and a monetary price, and grouped in actual districts. The initial population has a monetary yeary income, and a cultural string of 10 dimensions, the first two of which map ethnicity and religion. Both values are derived from the UK Census. We consider a location affordable if the price is less or equal to 6 times the annual income of an agent. This parameter will have to be explored further, especially in the light of the government encouraging the substantial expansion of credit to new homeowners. As for culture, the first two features of the culture string are fixed, while the remaining eight are susceptible to change as a consequence of interaction with neighbours, as in the abstract model. The up-scaled model also includes a *reserve* population pool, matching the ethnic composition and income structure of the UK at large. From this pool are drawn the agents migrating into the city at every time step, in order to simulate a plausible immigrant population.

The data sources employed, and the process of mapping geographical and socioeconomic data onto the model variables, are discussed in the following section.

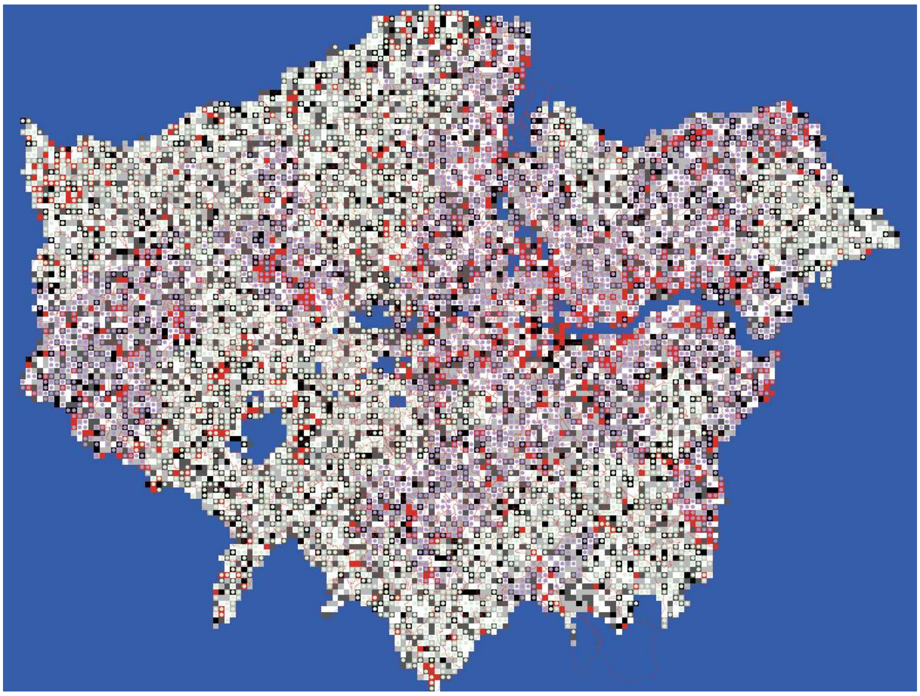


Fig. 3.4: The London urban area as represented in Netlogo

Table 3.5: Abstract - Empirical model location variables mapping

	Abstract		Empirical				
Variable	type, range	Value at initialisation	type, range	Value at initialisation	Data source	Level of detail	Description
r	float, {0,1}	random	float, {0,1}	empirical, from data source	UK Census Local environment deprivation idx	LSOA	Maintenance state
V	float, {0,1}	$r + 0.15$	integer	empirical, from data source	Zoopla.com / Land registry	Postcode	Value
G	float, {0,1}		integer		endogenous		Value-gap: difference with neighbourhood value
d	integer		integer		endogenous		Euclidean distance from centre of town
te	integer	random	integer	random	endogenous		Time empty
o	boolean		boolean		endogenous		Occupied?
s			boolean	empirical, from data source	UK Census Tenure	LSOA	Is social-housing?
oo			boolean		endogenous (true if occupied by owner)		Owner occupied?

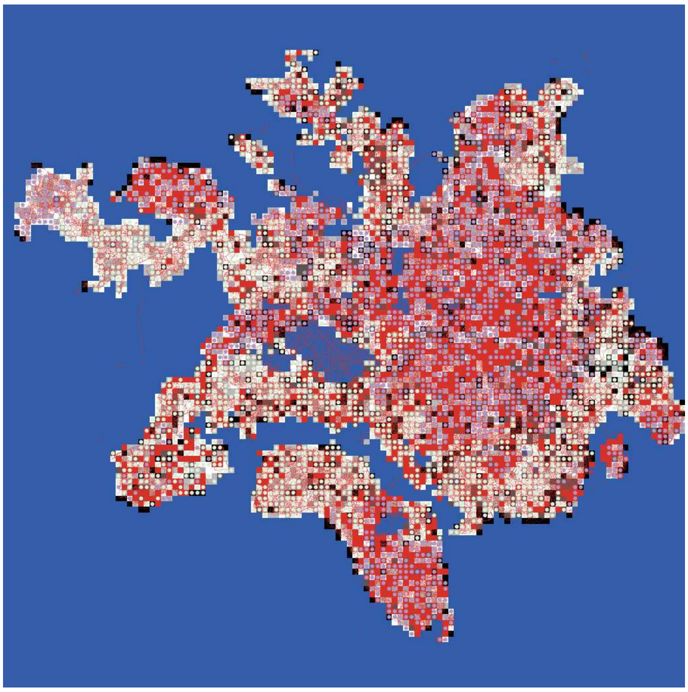


Fig. 3.5: The Manchester urban area represented in Netlogo

Table 3.6: Abstract - Empirical model agent variables mapping

	Abstract		Empirical			
Variable	type, range	Value at initialisation	type,range	Source	Level of detail	Description
m	float, {0,1}	random	float, {0,1}			mobility propensity
c	list t=10,v=4	random	list t=10,v=4	UK Census Religion Ethnicity	LSOA	culture: memetic code
i	float, {0,1}	random	integer	UK Census	MSOA	Income level
d	float, {0,1}	endogenous	float, {0,1}	calculated		Cognitive dissonance level
th	integer	random	integer	endogenous		Time here: (steps spent in the current location)
o			boolean	UK Census Tenure		Is home owner?

3.4.1 Embedding the data

Data sources: the UK Census, the Land Registry

The main data source employed to populate agent and location variables is the decennial UK Population Census, published by the Office for National Statistics. The Census includes data on demographics, economic activity, social conditions of the 52 million residents (2011) of England and Wales, released at different geographical scales, or *"Output Areas"*, in the classification of the ONS.

Super Output Areas (SOAs) are a set of geographical areas developed following the 2001 Census, initially to facilitate the calculation of the Indices of Deprivation 2004 and subsequently for a range of additional Neighbourhood Statistics (NeSS). The aim was to produce a set of areas of consistent size, whose boundaries would not change (unlike electoral wards), suitable for the publication of data such as the Indices of Deprivation. They are an aggregation of adjacent Output Areas with similar social characteristics. Lower Layer Super Output Areas (LSOAs) typically contain 4 to 6 OAs with a population of around 1500. Middle Layer Super Output Areas (MSOAs) on average have a population of 7,200. The hierarchy of Output Areas and the two tiers of Super Output Areas have become known as the Neighbourhood Statistics Geography.

As a prerequisite to embedding the data, we mapped LSOA and MSOA boundaries onto the city models in Figure 3.4 and 3.5, so that every location in the models has an LSOA, MSOA and PostCode attribute.

The built environment

The **maintenance state of dwellings** is a key variable in the model, as it determines the likelihood that a redevelopment will occur, and affects the mobility propensity of agents. Since the Census doesn't include a synthetic measure of the maintenance state of the housing stock, we identified the UK Census Living Environment Deprivation Index as the closest proxy. The Living Environment Deprivation Domain measures the quality of individuals‘ immediate surroundings, both within and outside the home. The indicators fall into two sub-domains: the "indoors" living environment, which measures the quality of housing, and the "outdoors" living environment which contains two measures relating to air quality and road traffic accidents. Four indicators are combined to calculate this domain, the indoors subdomain comprises of "Social and private housing in poor condition"; "Houses without central heating". The outdoors sub-domain: comprises of "Air quality" and "Road traffic accidents." As for the 2001 census this index was distributed including separate values for the two components: the "Housing in Poor Condition" indicator is described as the modelled probability that any house in a given area will fail to meet the ODPM 'Decent Homes' Standard'. The Central Heating Indicator is the percentage of households without central heating and is based on data from the 2001 Census. The Census included the question 'Does you accommodation have central heating?' and covered all forms including gas, oil, solid fuel, night storage heaters, warm air heating and underfloor heating (Indices of Deprivation 2004 Underlying Indicators: Living Environment). In the UK Census both indicators are released at the Lower Layer Super Output Area level.

These two indicators are mapped onto the r location variable. The mapping procedure in the model was performed via an iterative probabilistic procedure: for each LSOA a percentage of the locations matching the "Houses without central heating" value was assigned a random maintenance state below $r = 0.15$, and the "homes not meeting the decent homes standard" value was mapped as r being normally distributed between 0.15 and 0.35.

Census Variable	Model value
Houses without central heating	$m < 0.15$
Social and private housing in poor condition	$0.15 < m < 0.35$

Table 3.7: Built environment maintenance variables

The second crucial location variable is **price** (p). This was derived from the Land Registry "*Price Paid Data*[3]," which tracks residential property sales in England and Wales that are submitted to them for registration. Price paid data go back to 1995 and record the exact address and monetary price of every transaction. It is also used as the main source of Britain's House Price index. We populated the p variable of all locations in a postcode area with the median price paid value in that postcode area for a given year. Since most postcode areas map to only one location in the model, the procedure need not be more sophisticated, yet generates a very accurate mapping (given the scale of the model) of the house price structure of a city.

Agent variables

The main agent variables in the model are *income* (i) and *culture* (c). The Census variables used to inform these are three: *income*, *religion*, and *ethnic group*. Religion and ethnicity are mapped onto the first two items of the 10 dimension culture array, that represents an agent's "*memetype*,"

[3] https://www.gov.uk/government/statistical-data-sets/price-paid-data-downloads

as detailed in tables 3.8a and 3.8b. As the tables show to populate the culture attribute we grouped the 18 ethnic divisions existing in the Census in 4 macro groups (White, Black, Asian, Chinese) to match the 4 variations used in the abstract model. We then used a probabilistic iterative procedure to assign ethnicity to the population at LSOA level. The religion bit is assigned with the same method to the first bit of the cultural array. The four main religions of the UK are represented (Christianity, Islam, Judaism, Hinduism). These bits are not affected by interaction with other agents, and never change. They are used, nevertheless, when computing cognitive dissonance with neighbours. As for income, the UK Census stopped releasing income data in 2008. The last dataset available includes "model based estimates" of individual and household income at the MSOA level for the year 2008.

Religion	Agent variable
Christian	$c[0] = 0$
Muslim	$c[0] = 1$
Jewish	$c[0] = 2$
Hindu	$c[0] = 3$

(a) Religion

Ethnicity	Agent variable
White (British+Irish+Other)	$c[1] = 0$
Black (African+Caribbean+Other)	$c[1] = 1$
Asian (Indian+Pakistani+Bangladeshi)	$c[1] = 2$
East Asian (Chinese)	$c[1] = 3$

(b) Ethnicity

Table 3.8: Composition of the culture array

Social housing

An important addition to the empiric model, compared to the abstract version, is that of social housing. Social housing is a crucial feature of urban Britain and changes in the economic policy of the country over the last century have translated into changes in the role and provision of social housing. Stuart Hodkinson [49] observes that there has been a neoliberal turn away from the post-war collectivist model of public housing provision, towards private market and private financing arrangements. The privatisation of public housing began in the 1980s under the Conservative Government of Prime Minister Margaret Thatcher and has continued under subsequent governments through schemes as *Right-To-Buy*, which gives tenants of council housing the right to purchase and own their homes outright. This has translated into a steep depletion of the social housing stock of public rental housing: from 31.4% of housing stock in 1979 to 16.1% in 2012. Such reduction has had enormous implications on the (private) housing market. The model provides a powerful visualisation of many of these, discussed in Chapter 5, when presenting our case studies.

In our implementation, socially rented locations have the same attributes of other locations, however we assume that they are managed by the Government or other not for profit institution, therefore they: (1) won't receive private investment, (2) repair state won't decay below a certain threshold, (3) price will be assumed to be a fraction of the price of surrounding locations. We also assume that socially rented locations are not considered when computing price-gaps for surrounding locations. The rationale being that, when evaluating the potential return on investment, a developer would consider prices in the neighbourhood for properties with the same type of ownership. We also implement a rudimentary first-come-first-served housing waiting list: citizens who are not able to find an affordable location are housed in available social housing for a time of 50 years maximum.

With regards to the main dynamic implemented in the model, that of capital valorisation, we could argue that essentially - in our model just as in reality - social housing estates are *no-go areas*. They are often described as such in the popular press - "no-go areas" - referring to the supposed dangers and social problems that align in them. In reality, the peculiar characteristic that makes these areas inherently undesirable to the economic system - when observed with an *Olympic* view, in its fundamental workings - is that they are among the very few remaining places where (private) investment is not allowed to land. As the model vividly displays, social housing estates are locations where the white areas, symbolising the flowing of capital, never extend to. They are an obstacle to the process of capital reproduction, because they don't participate to the process of valorisation that lies at the basis of the capitalist mode of production. Chapter 5 elaborates further on this aspect.

3.4.2 Limitations of the up-scaled model

While the up-scaled model, compared to the abstract one, is driven by a greatly lesser degree of stochasticity and most parameters are populated with empiric and official data, it still remains grossly stylised and, in its current form, still suffers from a number of shortcomings that prevent its usability as a robust theoretical validation and planning support tool. The model does not implement at least three crucial features of urban systems: **population density**, **tenure**, and **land use**.

The lack of **density** (currently one modelled location can only accommodate one single agent) makes it impossible to model differences between central and suburban areas, and, crucially, to implement aspects of the capital valorisation process that might alter the density of a certain area. For instance, the landing of investment capital in a highly profitable area ought not necessarily result in the upgrading of existing properties, but could also translate in a wave of new builds - provided that room exists for expansion. This, in turn, would result in a slower process of displacement of the existing residents, a slower pace in the variation of the price structure, etc. Also, when modelling a crucial phenomenon of the past decades - the reduction of social housing provision - the lack of a density parameter means that a reduction of the proportion of publicly owned housing has to be implemented by removing existing social housing plots, whereas in many cities (Manchester is one case) such reduction is mostly the product of a densification of certain areas with privately owned new buildings.

Another important shortcoming is the lack of an implementation of different **tenures**. This results in a somehow cumbersome situation of a hybrid rental/purchase housing market, where agents can acquire a property if their income and credit allow it, but some agents are nevertheless deemed to be tenants and have to move out if the price of their home increases beyond a certain level. Moreover, different tenures impact in different ways on the decay rate of properties. It is generally assumed that owner-occupiers often tend to take better care of their property than tenants. This would change some dynamics of the mode, as certain areas would decline faster than others. **Tenure change** might take place in the case of landlords moving out of a declining area - a circumstance explicitly acknowledged in the rent-gap theory as a phase of the downfiltering process (see Section 2.3) - or deciding to let out a property in the case of prices rapidly rising in the area. In general, the impossibility to model different tenures and shifts between tenures prevents the emergence of certain dynamics that a model with an ambition of realism should include.

The assumption of a 100% residential space will also have to be dropped in a future version of the model. Allowing for different land uses and **land use change** is crucial to model post-industrial cities, where a substantial part of new building takes place on brownfield.

Despite these shortcomings, the up-scaled model is still a useful theoretical exploration tool in its current form, as we will show in Chapter 5. The implementation of the missing features is already underway, some of the variants (see Appendix) already developed include density and tenure.

3.5 Summary

Type	Variants		
Abstract (Sec.3.3)	Regeneration (Sec.4.4)	Beirut [73]	Sprawl (Appendix 7.1)
Up-scaled (Sec.3.4)	Manchester (Sec. 5.2.2)	London (Sec.5.2.3)	Pendleton (Sec. 5.3)

Table 3.9: Abstract and up-scaled model variants

In this chapter we described the main design principles of the proposed model of the Rent-Gap theory, and its variations. We built two versions of the model, an abstract/stylised one and a descriptive, "realistic" one. Table 3.9 below reviews the two models and their variants. In line with the agent based modelling tradition, the more abstract model is meant to explore basic patterns and processes triggered by a restricted set of theoretical assumptions. We proposed a few possible interpretations of the concept of "highest and best use" of a redeveloped property, and hypothesised on the interrelation of property investment and individual and household residential mobility. The *upscaled* model implements the same set of assumptions in a more "realistic" context, it is built using Geographical Information Systems and informed by empiric data derived from the UK Census and the Land Registry. The latter model will be used to attempt a validation of the theory in an actual urban context. The next two chapters present and discuss our results.

4

Results - The theoretical model

The conceptual model[1] described in 3.3 was designed to explore and possibly validate the founding principle of the rent-gap theory: that the primary driver of urban change is the pursuit of profit on the part of those holding capital. The model proposes a simple mechanism to simulate the circulation of capital in the urban system, and in this chapter we explore whether such mechanism produces emerging outcomes reminding of commonly observed urban dynamics. Initially, we perform a systematic exploration of the model's parameter space, highlighting the main dynamics that the model triggers.

The next section examines the basic dynamics of the model at the aggregate, city-scale, level, highlighting the most significant parameters. We test various parameters and monitor the effect on the price structure of the city, the number of locations keeping an acceptable level of maintenance, and the effect of culture. Section 4.2 discusses the intra-urban dynamics that the model generates and their relation with empirically observed phenomena.

4.1 General model dynamics at whole city scale

We typically run the model for 1200 steps, representing a 100 years time span, with the assumption of a constant value of K during the whole simulation time. Each parameter setting configuration is replicated 10 times and average values taken.

Here we test the main model parameters and highlight the effect that each of them has on the overall dynamic of the model.

[1] Parts of this chapter are based on [72]

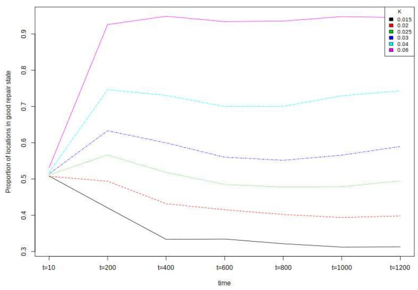
Table 4.1: Parameters and output

parameter	values tested	output
K	0.015; 0.025; 0.03; 0.04; 0.06	median city price; locations in disrepair
gap-setting mechanism	avg; max; new; lnd	
cultural exchange	On; Off	

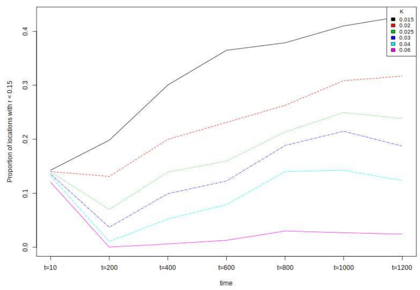
4.1.1 Effects of varying levels of capital

We start by exploring the effects that different levels of investment capital have on the urban environment.K is the total amount of monetary resources available in the economy for investment, expressed as the maximum fraction of locations potentially being redeveloped each year. We found the significant variable interval to be between $K = 0.01$ and $K = 0.07$. For levels below 0.01 prices collapse in every neighbourhood, all locations fall in disrepair, and the population disappears, as no location is inhabitable. For values above 0.07, all locations permanently achieve prices above 0.8, and almost no residents can afford to live in the in the city. We look at the dynamics emerging in the interval $0.015 < K < 0.06$.

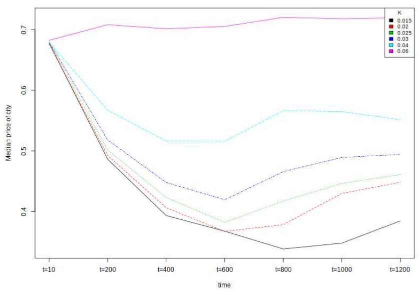
At the aggregate level, the diagrams below (Figure 4.1) show how the availability of capital has a direct impact on the number of well maintained locations in the city, the median price of the city, and, consequently, the median income of residents. Higher levels of capital correspond to larger numbers of locations receiving investment and being well maintained, and, conversely, to a lower number of locations falling in disrepair. At the same time, as K grows, the median price of property in the city also increases, with more locations increasing in value as they receive investment. Income follows the same pattern as the other variables: it is higher when K is higher, but Figure 4.1d shows an interesting phenomenon: the median income of residents is ever increasing, even in cases where median house price decreases. The reasons for this will become clearer when analysing price dynamics in individual districts in the following paragraphs, however the fundamental driver of this effect can be traced back to the different *command* that different social classes can exercise over space, as Neil Smith himself put it. At every cycle of investment in areas where prices go up, those with a higher income are allowed to stay, whereas those on a lower income have a higher probability of having to leave. The only circumstances in which agents leave their location are (1) if they are priced out, (2) when the cultural make-up of their area becomes excessively different, and (3) when the location turns into a slum. Therefore - even if investments slow down and prices, consequently, slowly decrease - the rich who inhabit pricey location never leave, until the very final “slumification” stage. This means that, as the simulation progresses, there’s an ever increasing chance that most available unoccupied locations will be either inhabitable (slums), or having recently experienced a price increase. Consequently immigrant agents[2] with a higher income have more choice, and a higher chance of finding a spot than those on a lower income.



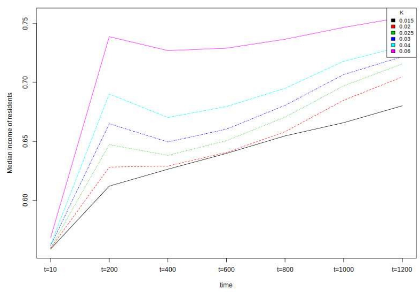
(a) Proportion of well maintained locations



(b) Proportion of locations in disrepair



(c) Median price of city



(d) Median income of residents

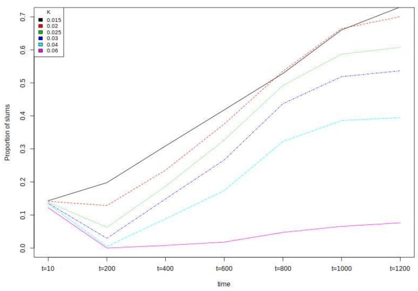
Fig. 4.1: *Effects of varying levels of capital* (average of 10 runs) - Higher levels of capital lead to a higher proportion of locations being well-maintained, a lower proportion of inhabitable locations, higher median price of the city, and higher median income of residents

4.1.2 Effects of different gap-setting mechanisms

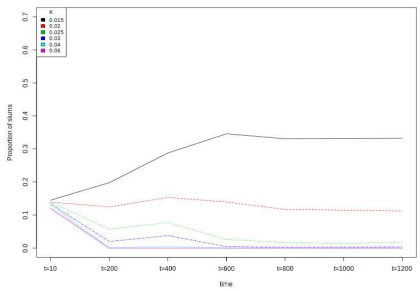
As discussed in the previous chapter, the gap-setting mechanism is an important parameter of the model, as it relates to the somewhat vague concept of *highest and best use*. In the original theory formulation, this is the maximum value that a property can attain once brought to the best

[2] Immigrants' income is generated randomly in the abstract model

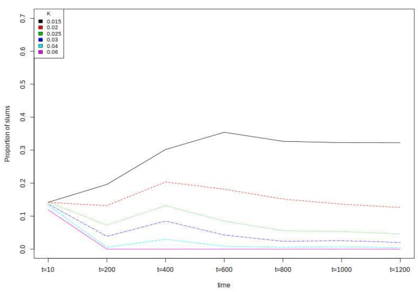
possible condition. We hypothesised four different methods to derive such value, all based on location constraints (see par. 3.3.1), and equally compatible with the theoretical formulation. Shown in Figure 4.2 and 4.3 is the effect of the gap setting mechanism on the amount of unmaintained locations and median city price. While the general effect of capital constraining the amount of locations being redeveloped is still apparent, the difference between mechanisms for setting gaps is also significant. Specifically, using the local mean as the upper price boundary after redevelopment, gave rise to a substantially larger number of locations in permanent disrepair for every level of capital, and a lower average city price. The reason for this is that, under the “*mean*” mechanism, capital tends to concentrate spatially to a much higher extent than with other mechanisms, for reasons that we detail in Section 4.2, where we look at inter-district dynamics. This produces a substantial uneven development between areas of the city whereby large areas fall in permanent disrepair, while few gain in value.



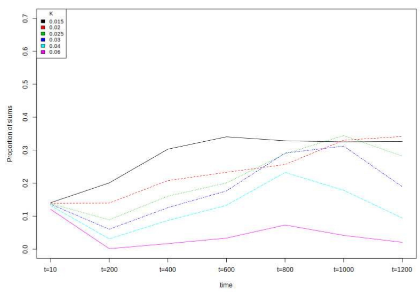
(a) Mean



(b) Max

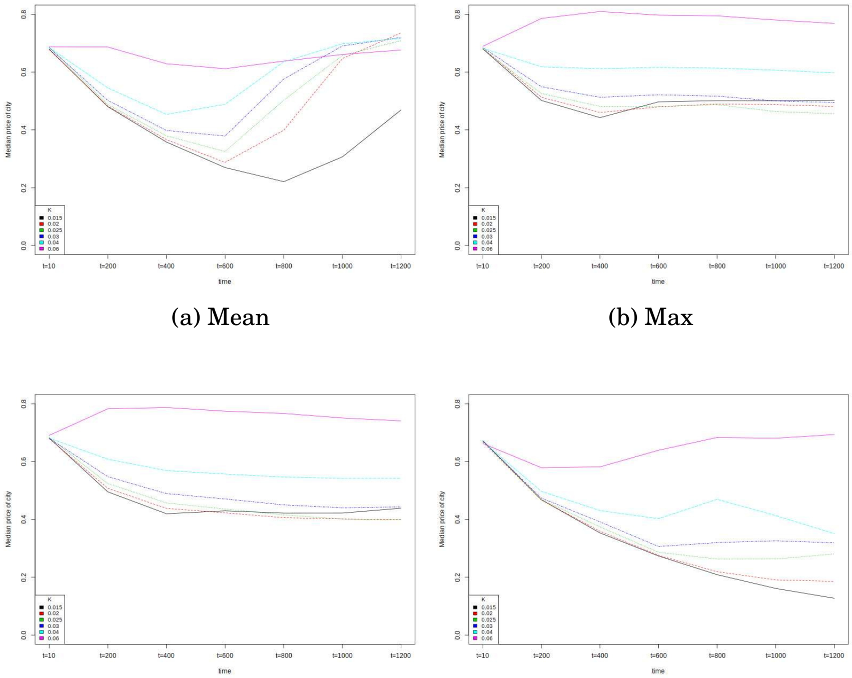


(c) New



(d) Lnd

Fig. 4.2: *Effect of different gap setting mechanisms:* proportion of locations in disrepair (average of 10 runs)



(a) Mean (b) Max

(c) New (d) Lnd

Fig. 4.3: *Effect of different gap setting mechanisms:* median price of city (average of 10 runs)

4.1.3 Effects of culture

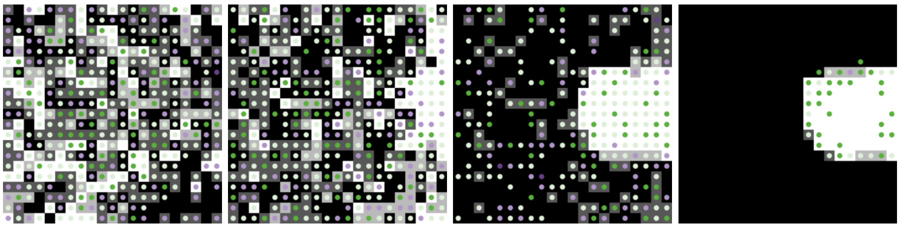
We also tested whether cultural interaction, as implemented in the model, has an effect on the dynamics of price. Completely switching off the cultural interaction module within the model - i.e. not allowing citizens to interact and modify their cultural string, and preventing them from selecting the place of residence based on the allure - does not have an observable effect on the dynamics of price. This is expected behaviour, and very much in line with the *supply side* nature of the Rent gap theory, which argues that the predominant driver of all that we call “urban dynamics” - including issues relating to the cultural and social composition of neighbourhoods - can be traced back to the needs of capital to circulate and regenerate. Urban dynamics are, in other words, a byproduct, or a dependant variable, of dynamics of capital circulation.

4.2 The intra-urban level - insight on economics

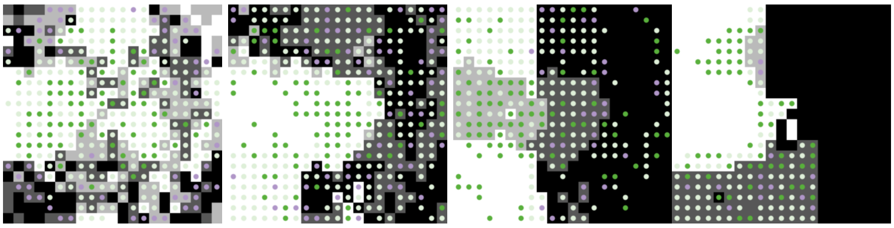
We now examine the spatial distribution of investments that different levels of K and the different systems of computing the rent-gap give rise to, at the intra-urban level. We will then show how the spatial dynamics of capital valorisation can determine the familiar phenomena of inner city decay and gentrification. In this model, as in the real world, capital has a dual role: a sufficient amount of capital is needed to ensure that a good proportion of properties in the city is maintained and habitable, but the nomadic nature of capital, which travels across the city in pursuit of the highest profit, generates shocks - in the form of abrupt spikes in prices and cycles of under-maintenance - which affect the ability of (especially least well off, who have limited choice) agents to stay in, or move to, the spot of choice. From this duality arise, ultimately, all the dynamics that we see occurring in the model.

4.2.1 Uneven development: spatial dynamics of capital and pockets of disinvestment

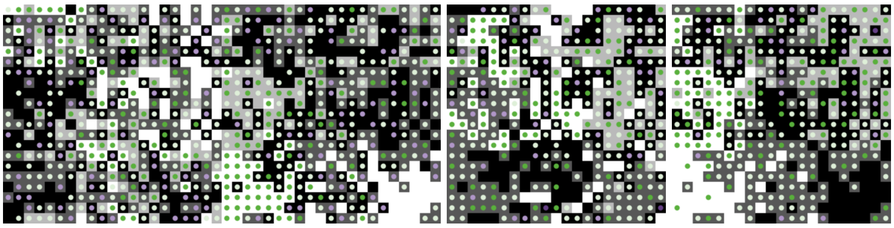
The most noteworthy dynamic produced by the model is related to the distribution of the redeveloped locations in the city throughout the simulation. All simulation runs start with a random distribution of prices and maintenance conditions across the city: the situation at $t = 0$ is similar to that represented in Figure 3.1. We observe that, regardless of the price-gap computation mechanism, the model shows a tendency of capital to first concentrate spatially, and subsequently moving “in bulk” across the city, in pursuit of the widest gaps between actual and potential prices. The level of capital determines the speed and the scope of the process, that can involve only certain areas or the entire city. Figures 4.4, 4.5 and 4.6 represent the spatial evolution of maintenance conditions and the corresponding price dynamics for different levels of capital and for the *mean* and *max* gap-setting mechanisms. As Figure 4.4 shows, after an initial period during which the locations attracting investment are scattered throughout the city, strong clustering emerges, visible as wide white areas representing areas of high maintenance and high price. This happens because the locations receiving investment increase their value and, when a large enough number of locations is increasing value in a small area, the rent-gaps of neighbouring locations widen, making them more likely to attract further investment themselves, thus generating a feedback loop. However, as capital is by definition limited, if investments start to concentrate in an area, inevitably other areas experience neglect, and a phase of decline starts elsewhere in the city. The decline ends when the price-gaps become “competitive” again, which happens mostly when all the gaps are closed in the previously “successful” area, and provided that enough capital is available. If so, investment moves on to settle in



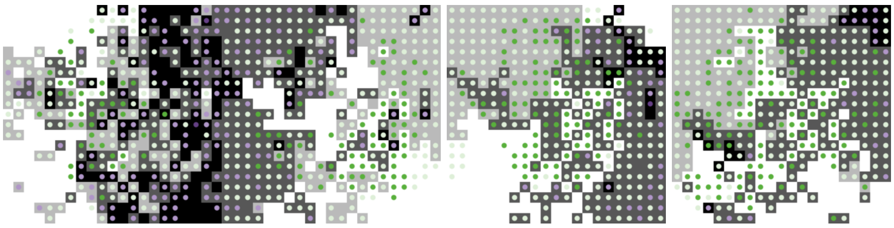
(a) $K = 0.015; t = 300$ (b) $K = 0.015; t = 600$ (c) $K = 0.015; t = 900$ (d) $K = 0.015; t = 1200$



(e) $K = 0.025; t = 300$ (f) $K = 0.025; t = 600$ (g) $K = 0.025; t = 900$ (h) $K = 0.025; t = 1200$

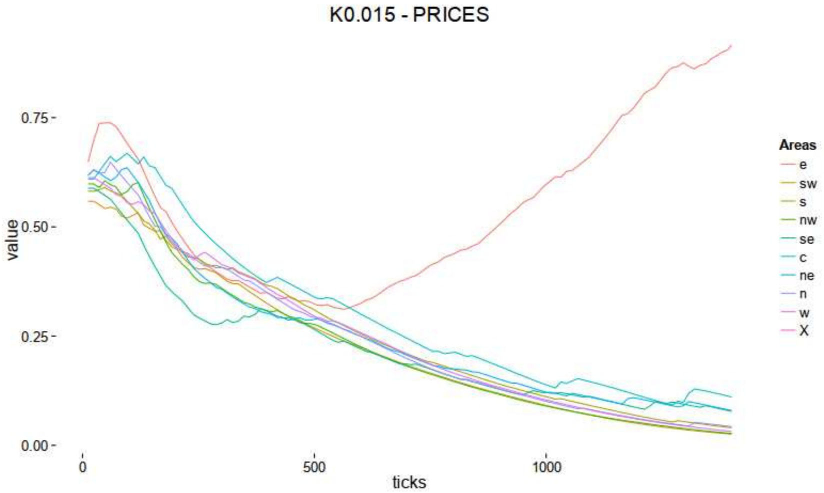


(i) $K = 0.015; t = 300$ (j) $K = 0.015; t = 600$ (k) $K = 0.015; t = 900$ (l) $K = 0.015; t = 1200$

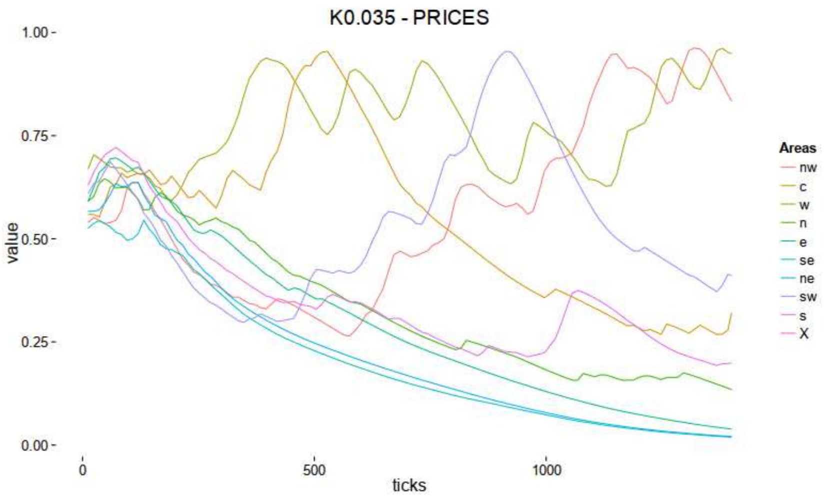


(m) $K = 0.025; t = 300$ (n) $K = 0.025; t = 600$ (o) $K = 0.025; t = 900$ (p) $K = 0.025; t = 1200$

Fig. 4.4: Evolution of maintenance condition for different levels of K and price-gap setting mechanism. (a-h) is based on average, (i-p) on maximum local prices. The circles represent agents, colour represents income in 4 shades: dark green, light green, dark violet, light violet in decreasing order.

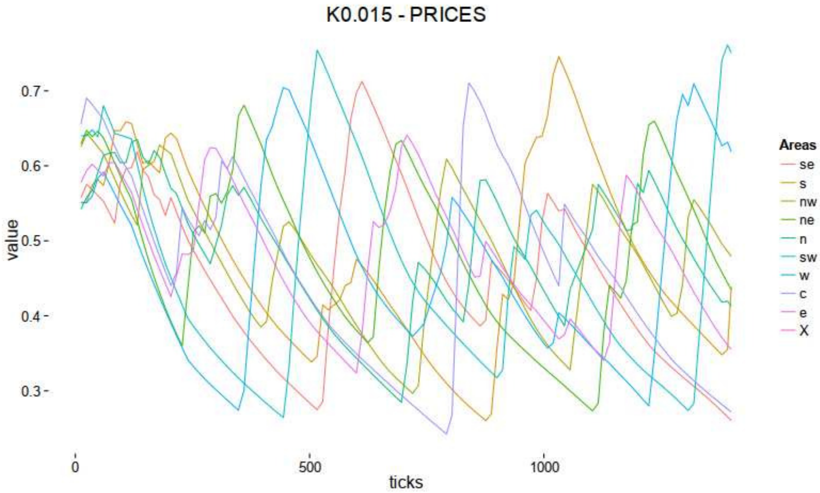


(a) $K = 0.015$, mean-based gaps

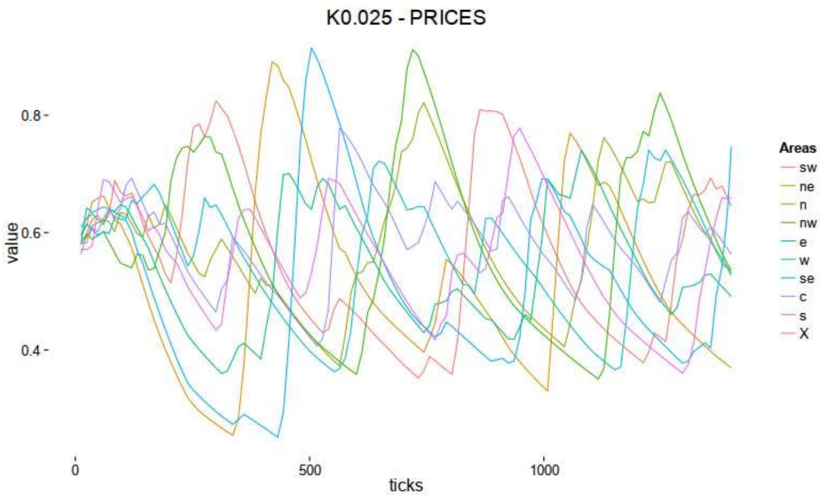


(b) $K = 0.025$, average-based gaps

Fig. 4.5: Price dynamics by district for different levels of capital under average based gap-setting mechanism. The tendency towards concentration and the cyclic trend of investment, disinvestment and reinvestment are evident. In the case of average-based gap setting, higher levels of capital correspond to more districts being involved in the cycles.



(a) K=0.015, maximum based gaps



(b) K=0.035, maximum based gaps

Fig. 4.6: Price dynamics by district for different levels of capital under maximum based gap-setting mechanism. When using maximum-based gaps, all the districts participate in the economic cycles even at lower levels of capital. Here higher capital corresponds to wider oscillations and higher prices

another area, generating the typical development cycles shown in Figure 4.5 and 4.6, matching Neil Smith's assertion that "*urban development in capitalist economies tends to involve a cyclical process of investment, disinvestment and reinvestment*". The overall effect is that of white areas "moving" across the city from neighbourhoods with narrow price gaps to those with wider price gaps. The dynamics produced by the model are a powerful intra-urban depiction of what David Harvey calls the *spatial fix,* or "the need of capital to try and displace systemic pressures onto other geographical areas" [45]: when investment becomes unprofitable in an area, because the existing rent gaps do not grant enough yield any more, capital has to move to a new area. This mechanism is ultimately the source of unevenness in the development of different areas in the same city.

Utilising the neighbourhood maximum, instead of average, as gaps-setting mechanism (i.e. using equation 3.2 in Section 3.3.1) generates a more fluid movement of capital that flows in the whole city even at low levels (Figure 4.6), while the *mean* method has a constricting effect, due to the lower number of location developing a positive price gap[3]. That concentrates the gaps - and therefore the profitable locations - in a limited area. In this case, for low levels of capital, only a limited set of districts are able to generate price-gaps wide enough to attract investment, and few districts participate in the economic cycles, while some others fall in permanent disrepair.

The fact that the model produces substantially different outcomes when using local maximum or local average as the price-gap setting mechanism - a difference not so fundamental, after all - seems to support the criticism that the RGT is too vaguely defined. It is also true that a clear-cut distinction between mean and maximum based price gaps is largely arbitrary. The two mechanisms could be at work at the same time in different areas of a city, for example responding to different demand levels: in popular, desirable areas an investor could charge the maximum local price for a restored property, whereas in areas of lower demand only the average could be successfully achieved. On the other hand, the model seems to disprove the argument of one of the fiercest critics of the rent-gap theory, Steven Bourassa. He pointed out that the existence of neighbourhoods which seem to never experience disinvestment contradicts the theory of the cyclical process of investment [19]. However the model shows that, in certain cases, a district can constantly achieve the highest rent-gaps within itself, and thus receive constant investment at the expense of the rest of the city, as is the case shown in Figure 4.5a.

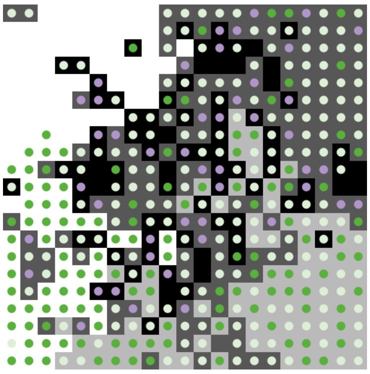
[3] The reason why under the *mean*-based mechanism fewer locations develop a positive price-gap is intuitive: few locations are priced below the average, more locations are priced below the maximum, by definition. This is shown with an example in paragraph 3.3.1

Also, for higher levels of capital, the emerging cyclical process of investment generates oscillations of different magnitude in different areas, so that some areas never reach a substantial level of disinvestment. Ultimately, spatial inequality is a constant dynamic emerging in the system, regardless of other considerations: *the simple assumption that prices tend to decay and profit-maximizing investment increases them, produces deep inequality between areas,* regardless of how revenues are measured and what is considered the "highest and best use."

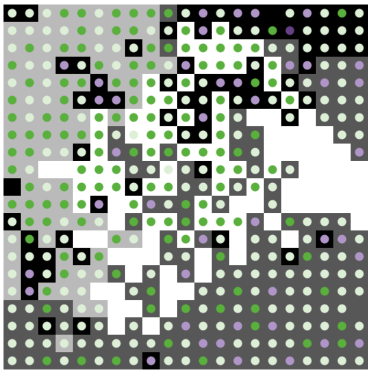
4.2.2 Cyclic decay and gentrification of the inner city core

One of the dynamics that have affected many cities in the Anglo-Saxon world for most of the 20th century is the slow decay of the inner core to the advantage of a sprawling and wealthy periphery. The "doughnut" cities see most of the wealth concentrated in the suburbs and an inner core in disrepair and populated by a low income, often predominantly immigrant, population. This tendency seems to have been reversed in the last decades, with the rapid gentrification of inner city areas. Most explanations of this phenomenon focus on the change of the social composition of cities - with a higher representation of white collar workers, who work in the city centre - and a consequent change of preferences in the younger population that now favours "city living" [58]. Another explanation sees this movement as supply, rather then demand, driven. It's the position that Neil Smith advanced in his seminal 1979 paper, titled in the most self-explanatory fashion, "gentrification: a back to the city movement by capital, not people" [83]. Figure 4.7c illustrates the emergence of this dynamic in the model: in this instance agents have a preference towards living near the core of the city[4], nonetheless the trajectories of capital make the best housing available at the periphery of the city for a substantial amount of time, and therefore the wealthy agents concentrate in the suburbs. When investing in the centre becomes profitable again, the reverse movement materialises and the inner city gentrifies. While the historic emergence of the doughnut effect took place in a phase of urban expansion, not implemented in this model (but expected in a future version, see 7.1) which only considers a fixed urban area with immutable boundaries, the model suggests that a cyclical *doughnut effect* can emerge endogenously, purely as a consequence of capital movements, without having to rely on demand-side explanations.

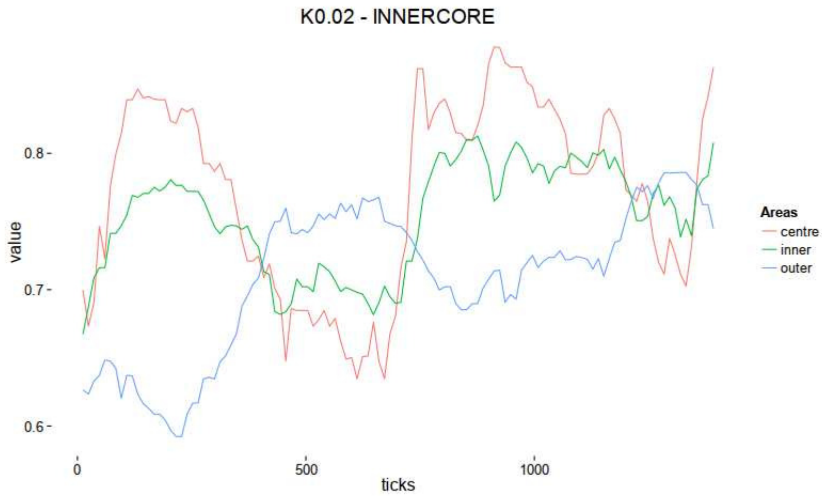
[4] The preference towards living in the city centre is implemented using the "global" centre in place of the "local" centre in the residential mobility process summarised in Figure 3.3



(a) t=600



(b) t=760



(c) Income levels of residents of the central, semicentral and peripheral areas

Fig. 4.7: **Decay and gentrification of the inner city** (K=0.02, max-based price gaps). In 4.7a the "doughnut" is formed and visible: the centre of the city is in bad repair state and populated by middle-low income agents. In 4.7b capital *moves back to the city* centre. The decline of incomes in the central area is steady for the first 500 ticks (red line in 4.7c), with the corresponding rise of wealthy agents in the periphery. The process of gentrification lasts less than 100 ticks, then a new cycle starts.

4.3 Cultural dynamics amid economic cycles

The fate of a district in terms of investment, development or decay is determined by the trajectories of capital, but the residential locations are also the background for the existence of agents and the cultural endowment that they carry. In this section we explore the dynamics of agents' cultural exchange while investment/disinvestment cycles unfold. The model starts with a random distribution of cultural traits in the population, and we will look at the circumstances that produce the emergence of culturally homogeneous areas and their sustaining through time. A culturally homogeneous area is defined as a district where the level of uniformity u as defined in Section 3.3.2 exceeds a threshold of 0.60.

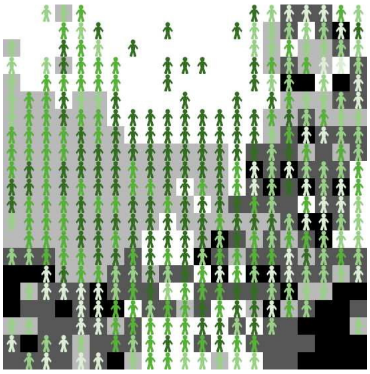
The interest in modelling culturally peculiar areas lies in the fact that, while they are often the most attractive areas of a city, the existence of cultural pockets tends to be very fragile: they are often the first to disappear as a consequence of economic shocks. Think of Prenzlauer-Berg in Berlin where, thanks to the large availability of cheap flats post-1991, a unique mix of radical minded younger people have been experimenting with innovative housing forms. Districts like Monti and Garbatella, in Rome, for a long time have been considered by Italians as cities within the city, with a distinctive feeling and even a local dialogue. The area of Hulme in Manchester, during the '70s and early '80s, gave birth to an entire music movement and its inhabitants developed a peculiar aesthetic and dress code [47]. However, as of today, price hikes in PrenzlauerBerg are limiting the freedom of experimenters, the increasingly gentrified Monti has driven away the delicate small-artisan ecosystem that gave the neighbourhood its unique feeling [48], and the demolition of the infamous Hulme Crescents by Manchester City Council took the style and the slang away with the blocks. We employed the model to explore the formation, development and sustaining of neighbourhood-level cultural identities as interstitial and transient phenomena resulting from cultural interactions between agents, interactions that do not happen in a vacuum, but are facilitated or disallowed by broad economic processes.

Because the only source of homogeneity in the model is prolonged interaction between neighbouring agents, the initial emergence of a culturally homogeneous neighbourhood, under the residential mobility conditions resumed in Figure 3.3, depends on the prolonged availability of decent ($r > 0.15$) housing at a medium/low price. Long periods of stable or decreasing prices allow the agents to stay put and interact, becoming more and more similar. However homogeneity is rarely attained in low capital conditions. With low capital, investment clusters late in the simulation: for the first 500 steps or so the locations being renovated are scattered across the city. This results in agents being removed from their location due to price increases almost at random, and this quasi-random removal of agents prevents uniformity to emerge. For higher levels of capital, on the contrary, investment waves take place early in the model. In this case in the phases of declining or stagnating prices, districts are likely to develop high cultural uniformity because the agents can reside there almost undisturbed. When the cultural uniformity of a district reaches a threshold ($u > 0.60$) the district develops the *allure* attribute, which becomes visible to all agents. Once this happens, agents seeking location can consider moving there on the grounds of cultural homophily.

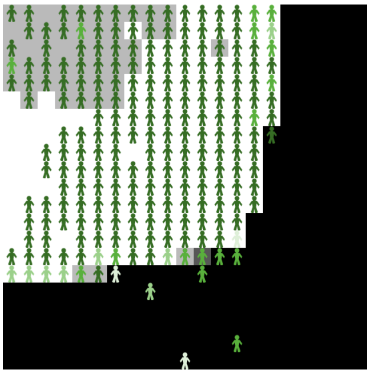
Table 4.2: Trend in culturally uniform districts after allure has emerged depending on subsequent price movement

Original price	Price trend	
	Downwards	Upwards
High	Dissolution by immigration	Reinforcement by self-selection (Fig. 4.9)
Low	Dissolution by slumification (Fig. 4.8)	Dissolution by gentrification (Fig. 4.10)

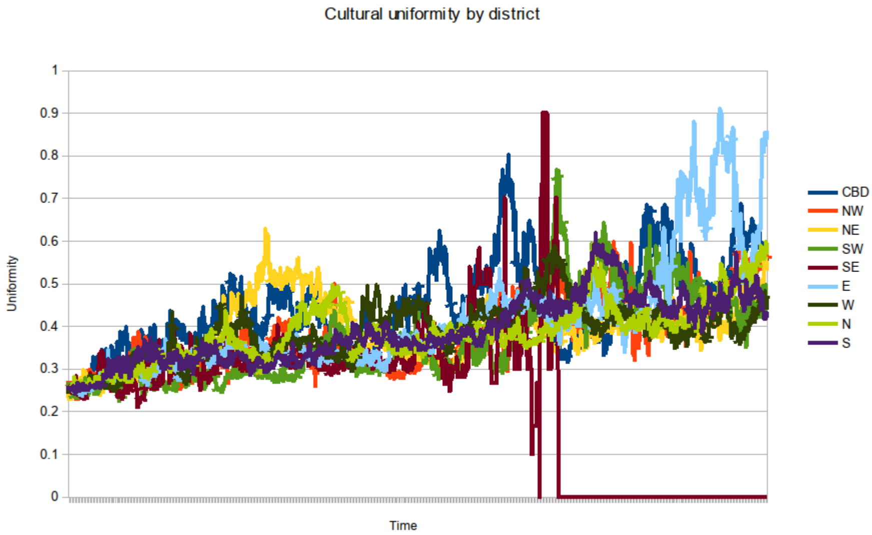
The follow-up to the emergence of an allure depends on the interplay between the price dynamics of the area and those of the rest of the city. Table 4.2 summarises the effect that price changes have on cultural uniformity as they appear more frequently in the model. If no investment reaches an area, prices keep falling and the dwellings keep decaying, eventually the community dissolves, because agents have limited tolerance towards living in a slum ($m < 0.15$). It is the case depicted in Figure 4.8. If, on the contrary, prices start to rise, as a consequence of capital flowing in, the place is bound to gentrify and is very likely to lose its cultural uniformity. The fate of many a working class neighbourhood fall in this category, shown in Figure 4.10. Here district S, an area of low-middle income made up of mostly ageing buildings, develops an allure at t=984. Shortly after prices start to rise, as a consequence of capital flowing in. The abrupt spike in prices that takes place afterwords (4.10e) forces the least affluent residents out of the area and brings in new residents with an higher income (4.10d). Such rapid population change dissolves cultural uniformity in the area, which is now more affluent and less culturally recognisable. Gentrification does not always dissolve cultural homogeneity, though. At this stage much also depends on the processes going on in the rest of the city. If other neighbourhoods in the city are decaying, for example, an outflow of agents is to be expected, and since there is one culturally recognisable neighbourhood, some agents can relocate to a location that reflects better their cultural makeup, reinforcing, instead of destroying homogeneity. When this happens the neighbourhood will keep its high cultural uniformity, but the population will also become uniform



(a) t=395 - Emergence of allure



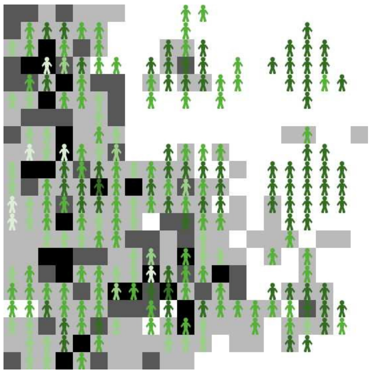
(b) t=1200 End state of city



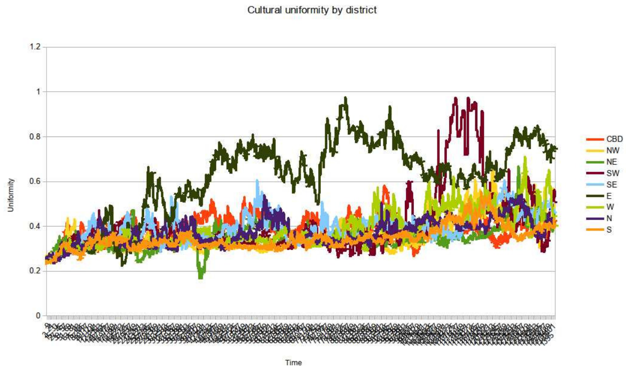
(c) Cultural uniformity by district.

Fig. 4.8: Dissolution by slumification. Early uniformity in district NE (yellow curve in 4.8c) dissolves due to lack of investment and conditions deteriorating: when most of the area turns into a slum agents leave.

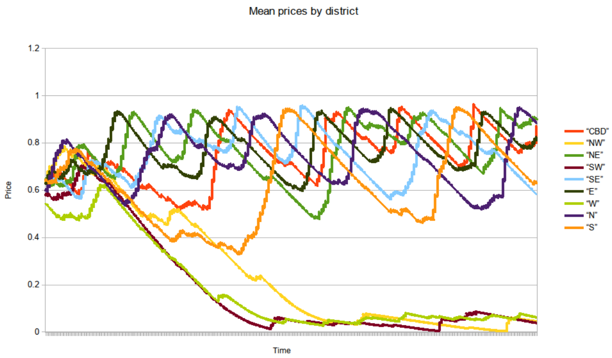
in terms of income. Correlation between decreasing prices in one area and increasing uniformity in another is frequent, signalling that this is a recurring dynamic.



(a) Allure emerges in district E at t=279



(b) Cultural uniformity by district.



(c) Prices by district

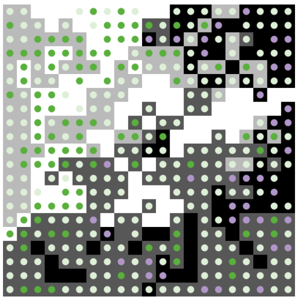
Fig. 4.9: Reinforcement by self-selection. Allure emerged in high maintenance district "E" (4.9a) is sustained across all the simulation (4.9b). Prices in the district remain at a high level, allowing for little immigration. Lower prices in other districts increase the probability of newcomers being motivated by the allure of the district, therefore increasing uniformity.

The decay of other parts of town is not a necessary condition for a homogeneous community to resurface after gentrification. In some instances the model displayed a process sometimes described as recolonisation. In such case a culturally homogeneous community re-surfaces after a gentrification process but, contrary to the original community, the new one is wealthy and homogeneous with regards to income as well as culture. A similar dynamic is described by Sharon Zukin in *Naked Cities* [94] in Chapter 2. It took place in Harlem between the late 1980s and the early 2000, when a new population of wealthy blacks who claimed their "ideal roots" in Harlem displaced the original less affluent black community that had *actual* roots in the neighbourhood.

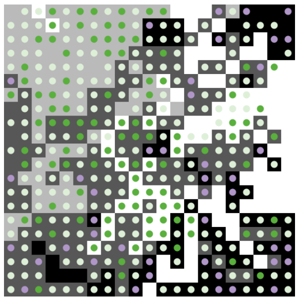
In general, abrupt shifts in prices seem to always have a disruptive effect on cultural homogeneity. A high-prices + high-uniformity district, where prices start to fall, sees an influx of newcomers which dilutes uniformity. A low-price + high-uniformity district, where prices start to rise, displaces some of the residents. Ultimately, as the results table above suggests, in this model cultural uniformity is nearly always a transient phenomenon, destined to disappear in the long run. A phenomenon that only exists under conditions that are bound to change - those of slow, prolonged, gentle decline in prices. This is partly due to implementation limits, the absence of tenure being the most significant (the model is "all-rental" - see Section 3.3.3). In presence of a proportion of the population occupying own homes, all the dynamics described above would unfold - at least - at a slower pace, as only a smaller share of residents would be forced to move out in case of a price hike. Also, it might be argued that the rate of decline in maintenance level would be different between owner-occupied and rental properties, this could also change the pace and scope of the dynamics that emerge in the model. A future version, with a more realistic implementation of tenure, would have to explore cultural dynamics under various scenarios of tenure structure.

4.4 Modelling regeneration

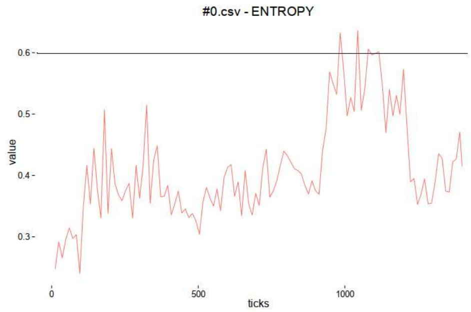
In Section 4.2 we described the spatial dynamics emerging from different levels of capital invested in the city under different methods of computing the rent-gaps. Starting from a random situation such as that in Figure 3.1a, the model highlighted the tendency of capital to spatially concentrate and subsequently "move" in waves around the city in pursuit of the highest profit, producing enduring inequalities in investment and therefore in maintenance state, between areas. The dynamic of prices across the city were strongly reminding of the oscillations theorised by Smith. In cases of low inflow of capital the model showed certain areas of the city suffering permanent under maintenance, because the rent-gaps that develop in such areas are too narrow to guarantee a profit. It is the situation depicted in Figure 4.11, which represents the city at $t = 417$ with $K = 0.035$ under a *mean* gap setting mechanism. The one depicted in Figure 4.11 is the typical situation that would call for a urban regeneration



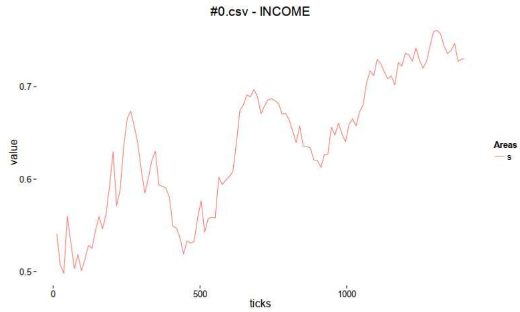
(a) t=984 Allure emerges in S



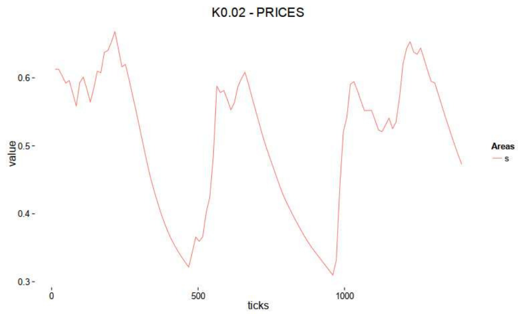
(b) t=1080 Gentrification of S



(c) Uniformity in district S



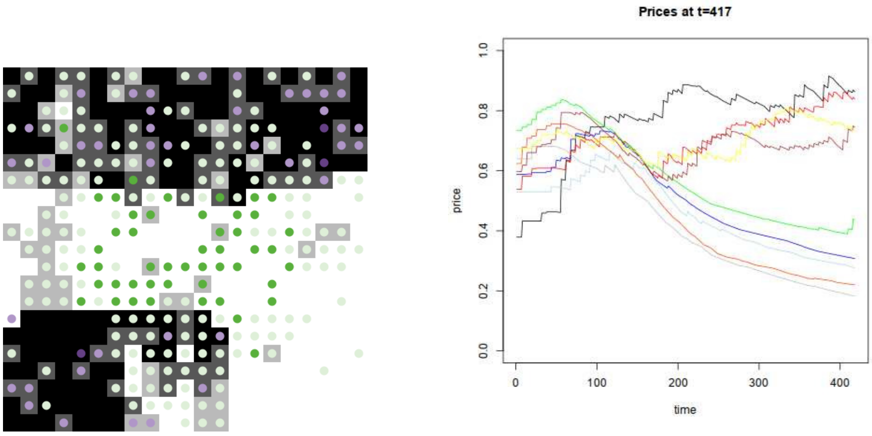
(d) Average income of district S



(e) Mean prices of district S

Fig. 4.10: Dissolution by gentrification. District S develops an allure at t=959, gentrification starts at t=1080. The spike in prices (4.10e) forces the least affluent residents out of the area and brings in new residents with an higher income (4.10d). Such rapid population change dissolves cultural uniformity in the area.

programme: an under maintained area with very low property values and ongoing de-population. For this exercise we take that as a starting point to simulate the regeneration of a run-down area under the theoretical constraints that we assumed.



(a) t=417

(b) Evolution of price levels from t=0 to t=417

Fig. 4.11: k=0.035. Neighbourhoods C,E,W and SE capture all the investment capital available, achieving high maintenance and high prices. Neighbourhoods N, NE, NW and SW (bottom grey line) see prices and maintenance condition decline and progressive depopulation, as agents leave undermaintained properties.

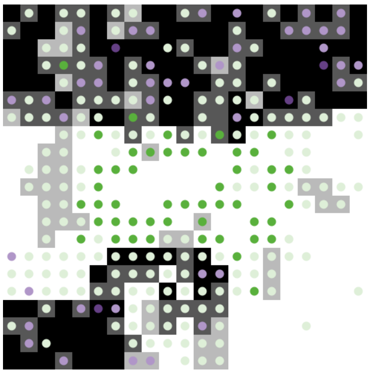
Broadly, urban regeneration is usually described as a set of policies and interventions aimed at the improvement of neglected urban areas, with the intent to revitalise deprived communities, renovate the housing stock, varying the social composition and, ultimately, rendering the area more palatable for private sector investment. Urban regeneration takes often the form of mixed public and private partnerships, a formula known in the UK as "Private Finance Initiative", or PFI, whereby the government invest public money in the purchase of properties in decaying areas from private owners, and then hand them to developers for very little o no price, for restoration or rebuilding [18]. The desired effect is that an area incapable of attracting investment is suddenly *kick-started:* properties are upgraded, prices generally increase, the social composition changes and, ideally, the effect reverberates on neighbouring areas.

Within our conceptualisation of the city and its economic dynamic, we could conceive publicly funded regeneration programmes as having the ultimate effect of *artificially* raising the prices of low value areas outside of the normal private investment mechanic implemented in the model as described in the previous chapter. The *artificial* raise in prices of certain locations, in turn, has the side effect of generating rent-gaps where there are none, opening up the possibility for capital to move in to close them and, as a consequence, bring a wider area to higher maintenance conditions and economic value: in this sens regeneration, literally, *opens new spaces for capital*. In order to represent such an intervention in the model we raise the level of maintenance of a decayed area - identified deterministically as the 9 contiguous locations with the lowest value and maintenance level of the city - to $r = 0.95$ and bring the price of such area up to the city average. In the case in question all the locations with the lowest value and maintenance level fall in neighbourhood SW, the bottom left quadrant of Figure 4.11a.

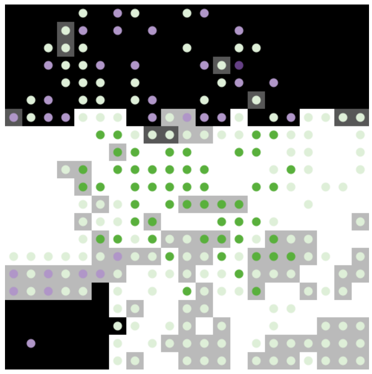
We found the effects of such measure to vary depending on the level of decline reached by the affected area. In the example provided, regeneration alone proved insufficient to trigger a renaissance of the area. In most cases, as Figure 4.12 shows, the regenerated area couldn't sustain the new prices and maintenance levels in the long term, and ended in decay. A level of investments that has not guaranteed development across the whole city, in this model, cannot be overturned by simply restoring an area. The opposite is also true. A substantial increase in the capital available is also not enough to rescue a neighbourhood that has reached the lowest level of price and maintenance, because if the area is not capable to attain lucrative rent-gaps, the higher capital level will have the effect of flowing elsewhere in the city, where the most profitable rent-gaps exist, raising the prices there. Figure 4.13 shows this circumstance: here capital has been raised to $K = 0.055$ at $t = 418$, the effect is prices going up in the already well developed districts of the city and falling further in SW. However, we found that the combined influx of capital and regeneration has the effect of bringing a completely declined district back into the investment cycles in most runs (Figure 4.14).

4.5 Conclusion and summary

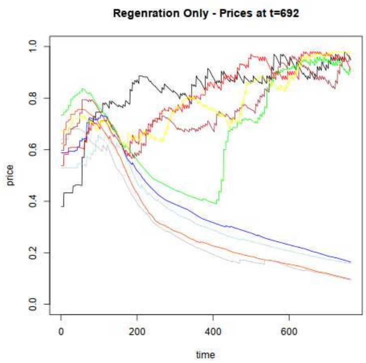
The abstract implementation of the rent-gap theory presented in this chapter was capable of showing emergent features vividly reminescent of real-world dynamics documented in the last century of urbanisation. We could reproduce cycles of investment and disinvestment in the central urban core, followed by waves of gentrification and social down-filtering. These mimic the evolution of north American urban areas in the XX century, with a phase of suburbanisation of wealth between the 60s and 80s and a subsequent "back to the city" movement. We believe that our results show that an alternative interpretation of urban dynamics, seen as con-



(a) t=418 - The 9 location at the top of the SW quadrant become white (well maintained)

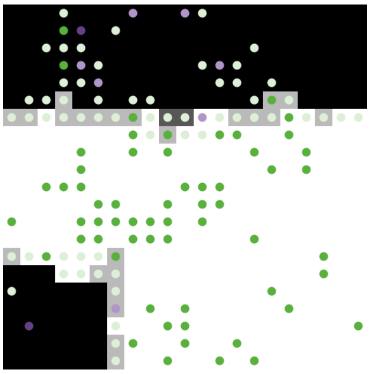


(b) t=692 - The regeneration hasn't had a beneficial effect on the rest of the SW area, which stayed in bad repair (black) and the locations restored are declining again (they are now grey).

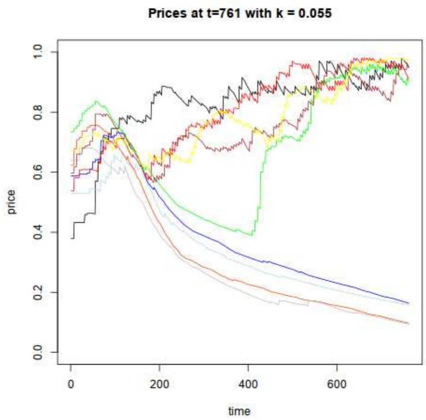


(c) Price levels in the 9 neighbourhoods across the simulation. SW is the grey curve. An increase is visible at the time of the regeneration, but in the longer term the prices continue their decline

Fig. 4.12: Regeneration without capital increase - Increasing price and maintenance level for 9 locations in neighbourhood SW at t=417. This intervention has a marginal effect, limited to the interested area, nine locations at the top of the SW quadrant, which turn white (=well maintained) and attract new residents, but decline in the long term.

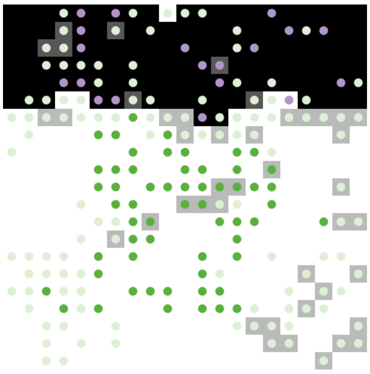


(a) City situation at t=761

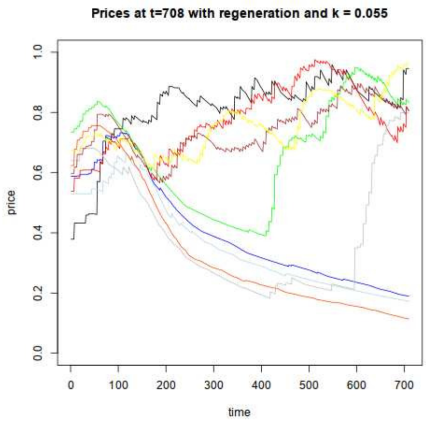


(b) Price levels across the simulation. SW is the grey curve

Fig. 4.13: Capital increase without regeneration t=761 - k=0.055



(a) t=664



(b) Price trend

Fig. 4.14: Regeneration, plus capital increase at t=664. In this case we regenerate 9 locations in SW and set k=0.055. The white area spreads to all the declining neighbourhood and prices rise very quickly, as capital has moved in.

sequences of the mechanics of capital circulation, is - at least - plausible in principle.

The model was also useful to explore the impact of economic cycles on the social and cultural make up of a stylised city and to visualise the mechanics of urban regeneration. The number of theoretical exercises that this implementation of the RGT allows for doesn't end here. An extension to the model currently in the works will also simulate the phenomenon of suburban sprawl, emerging in a city in expansion, still as purely the product of the simple mechanics of capital circulation (see Appendix).

In the next chapter we "upscale" the model, and test it in a more realistic, data-driven setting.

5

The up-scaled model: validation and case studies

5.1 Introduction

The up-scaled model[1] implements the same core dynamics of the "abstract" version presented in Chapter 3.3 and 4. This version runs on a GIS representation of an actual urban area, with a lesser degree of stochasticity, and most parameters are informed by empirical data. We described the process by which the abstract model variables were populated with empirical data in Section 3.4. The purpose of the up-scaled model is primarily to test the validity of the theory in a more realistic context than a square grid. Also, we wish to explore the potential of this model to serve as a planning aid tool: a tool to perform scenario analysis and help in the assessment of the possible outcomes of urban regeneration programmes.

5.2 Model validation

5.2.1 The validation of agent-based models

Validation constitutes one of the central problems of computer simulation methods. It relates to the extent to which the model adequately represents the system being modelled [23] and in this sense, it involves the goodness of fit of the model to data. Simulating is to use the computer as an artificial laboratory in which basic causal relationships can be tested in order to gain some knowledge on the underlying (much more intricate and convoluted) real-world causal structure, but there is a constant danger of building auto-referential formalisations that have no link to reality [33]. There is a wide variety of accounts of different strategies for validating

[1] Parts of this chapter are based on [71, 72]

simulations in social sciences. The so-called 'cross validation' [62] suggests developing the simulation at the micro-level based on qualitative evidence, then validating it at the macro level against independent data. Grimm [42] recommends the multiple validation of simulations, whereby a simulation matches many sets of qualitative validation simultaneously. One of the most routinely conducted evaluations of a model is to assess its predictions against independent observational data. This 'confrontation' is what traditional model validation comprises, can be achieved using many methods, but generally includes four components: (1) the observational data that will be used to evaluate the model; (2) a summary of the data, such as mean trajectories and patterns, and probability distributions of observed and predicted data; (3) measures used to make a decision about whether or not to accept the model, such as qualitative comparison, visualisations, difference summaries and formal statistical testing; finally (4) a decision, based on the measures in the previous step, as to whether the model's performance is adequate given the context in which it will be used ([68], p.212).

However, the validity of a model should not be thought of as binary event (i.e. a model cannot simply be classified as valid or invalid); a model can have a certain degree of validity which of course is encapsulated by various measures of fit. In our case, since the rent-gap theory is essentially a theory of capital motion, the main objective of validation is to assess whether the model can accurately identify the areas where investment is likely to land and, consequently, bring about a price increase. The observational data employed to validate the model is the variation in house prices between years 2001 and 2015, obtained from the Land Registry, and observed on a decidedly granular scale - Medium Layer Super Output Areas (MSOAs). Our validation will consist in attempting to reproduce the observed evolution of prices, initialising the model with the situation at year 2001 and comparing the results with the situation at year 2015: essentially we are trying to reproduce a historic trend. We attempted a validation in two settings, Manchester and London, in the UK, described in the following two sections.

5.2.2 Manchester

Delimiting the urban area in which to base the model was the first non trivial task of the endeavour, as the Mancunian conurbation does not have obvious boundaries. Once we ruled out using the administrative limits of the very oddly shaped Manchester city council, and those of the Greater Manchester county - which contains at least three other clearly independent urban cores - we opted to consider "Manchester" the area enclosed by the M60 motorway. The M60 effectively acts as an outer ring road for the urban area, however certain areas not enclosed by the M60 were also included, on the basis that they either (1)

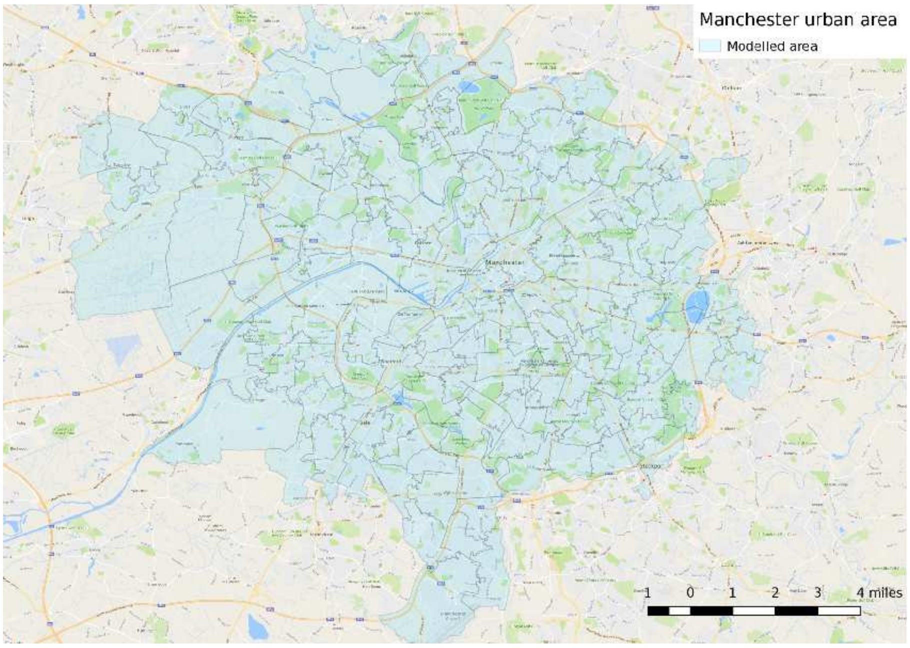


Fig. 5.1: The modelled area within Greater Manchester, divided in 142 MSOAs

fall within the Manchester City Council jurisdiction, or (2) are reached by Manchester's tram network and don't lie close to a recognisable city centre different from Manchester's. The area modelled is shown in Figure 5.1.

As mentioned above, our style of validation consists in trying to reproduce the historical evolution of prices across the study area. We obtained Land Registry price paid data for the years 2001 and 2015, grouped them by MSOA and calculated the 2001-2015 variation according to the formula $\Delta p = \frac{p^{t1} - p^t}{p^t}$ where $t = year2001$ and $t^1 = year2015$. We then initialised the model with price paid data for the year 2001, and the social composition (income and ethnicity) of Manchester's neighbourhoods derived from the 2001 UK Census. The model was run for 156 steps (months) testing the parameter combinations in Table 5.1. Each parameter combination was run 10 times and the average value

parameter	values	
K	0.015	0.03
gap mechanism	mean	max
immigration	0.015	0.03
reduction of social housing	true	false

Table 5.1: Validation parameters

taken as result. We then calculated the variation in prices resulting from the simulation according to the same formula: $\Delta p_s = \frac{p_s^{t=156} - p^t}{p^t}$ where p_s is the simulated price. Our "capital" estimation, $K = 0.03$, was based on the increase of the dwelling stock of the last decade, which has been of 1.5% yearly, plus an estimate on the restoration of the existing stock of a further 1.5% per year. The value of K was halved between step 84 and step 130, modelling the credit crunch and the drastic reduction in housing investment between 2008 and 2012.

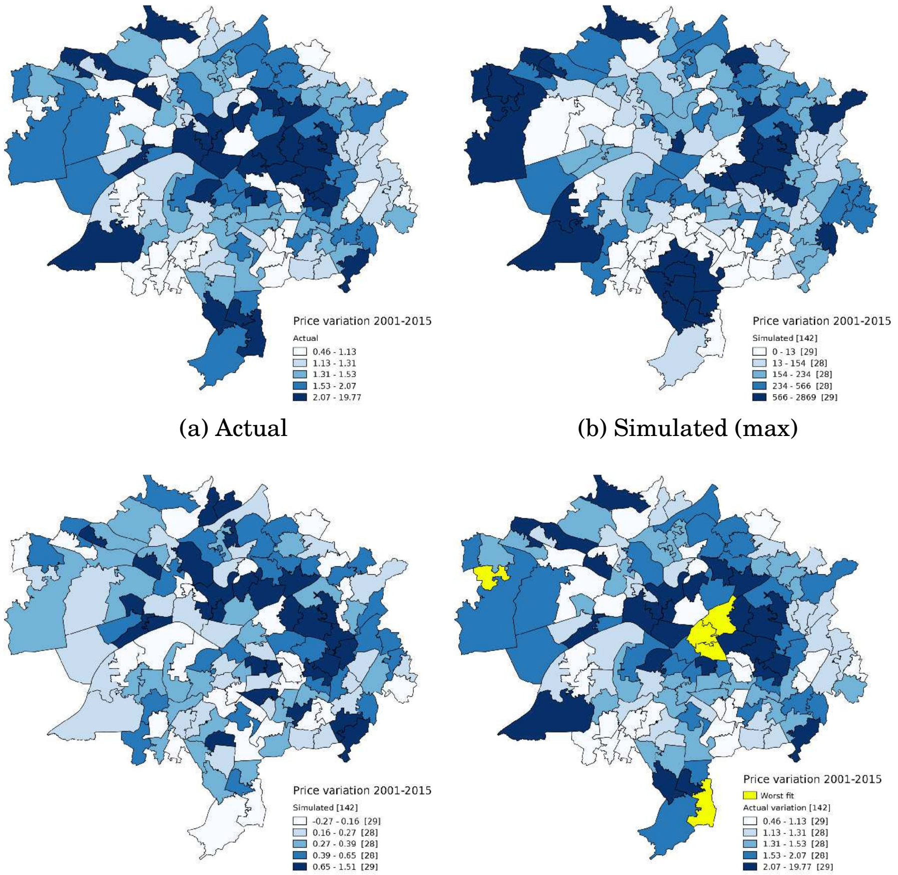
Because the main aim of this exploration is to identify the areas of the city where investment will likely land and generate an increase in house prices, we compared the distribution of Δp and Δp_s, the actual variations in price occurred across the 142 MSOAs of the Manchester study area, with those resulting from the simulation. Figure 5.2 shows the comparison between the actual price variation and the best fitting combinations of parameters, i.e. the combination of parameters that most closely match the actual variation. The 142 MSOAs are grouped in 5 quantiles of the same range of variation. The model was capable of accurately reproducing the assignment of nearly 40% of the MSOAS to the appropriate quintile (i.e. the same quintile in which they fall in empirical data). Including MSOAs with a discrepancy of only one quintile (i.e. MSOAs that fall in the 2nd quintile in empirical data and 3rd quintile in the simulation, or 5th vs 4th), the model accounts for over 72% of the entire urban area (Table 5.2a). The 5 MSOAs with the highest discrepancies between actual and simulated data are highlighted in Figure 5.2d. The three contiguous areas towards the middle of the area are Manchester city centre, the Northern Quarter, and the University/Oxford road area - the model greatly underestimates the growth in price of these areas. These are not ordinary residential ares though. It might be argued that the dynamics of investment in these particular areas follow specific patterns that the model is not (yet) capable of reproducing.

5.2.3 London

The same validation approach was adopted to test the model on the Greater London area, a much larger urban area comprising of 945 MSOAs. The model was run with $K = 0.15$, or five times the Manchester value, and $i = 0.06$. The results in Figure 5.3 are relative to a run using average-based price gaps. The fit here is also encouraging, Table 5.2c shows that a third of the MSOAs match the quintile of the empiric data, and another 40% is only one quintile distant.

5.2.4 Discussion

Our simulated patterns show significant similarities with the actual evolution of the price structure. The model seems to be able to reproduce

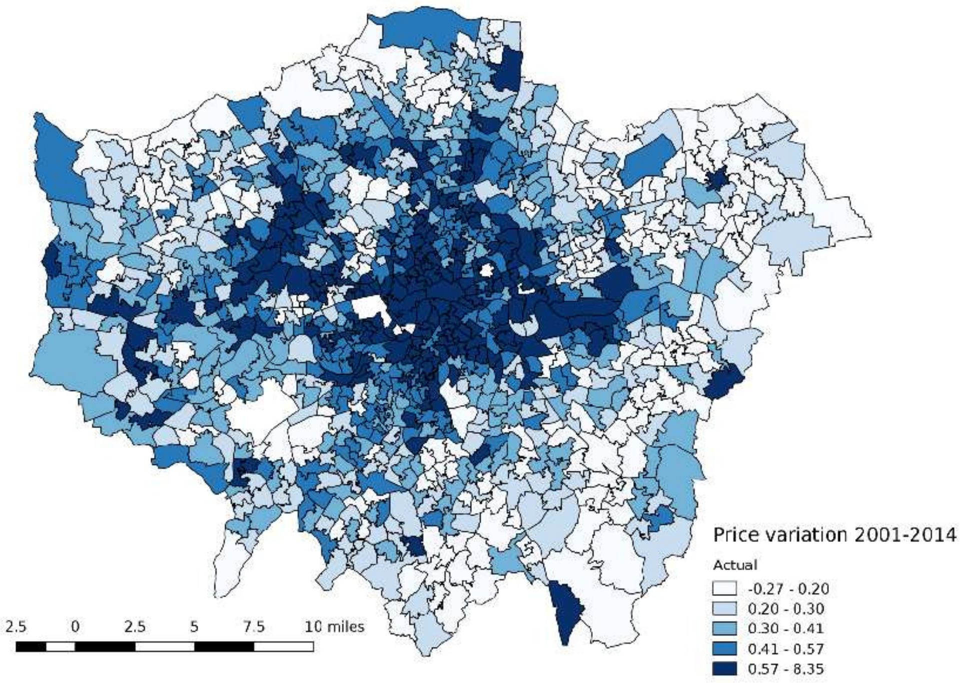


(a) Actual (b) Simulated (max)

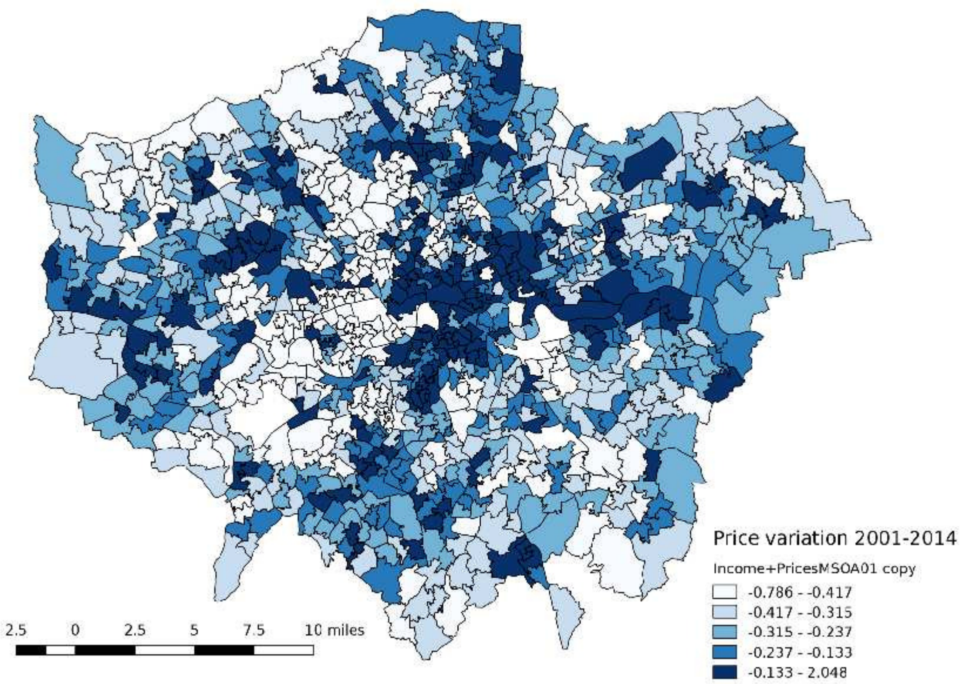
(c) Simulated (mean) (d) MSOAs with the worst fit

Fig. 5.2: Variation in house prices in Manchester 2001 - 2015, actual and simulated.

the flow of capital into certain areas rather than others with an encouraging degree of accuracy. However, significant differences exist between the magnitude of actual and simulated price variations. These are not accurately reproduced when the model is run under a maximum based gap setting mechanism, in which case the increase in prices is greatly overestimated. The mean-based gap setting mechanism produces variations in price more consistent with the observed ones, but produces a worse fit in terms of distribution of investments. However, bearing in mind the numerous limitations of the up-scaled model (see Section 3.4.2), it is our opinion that the results obtained with the current implementation - run without any form of ad-hoc tuning, with an ultimately fairly simple mech-



(a) actual



(b) simulated

Fig. 5.3: Variation in house prices in London 2001 - 2014

mismatch	frequency	%
0	55	38.7
1	47	33
2	22	15.4
3	13	9.1
4	5	3.5
total	142	100

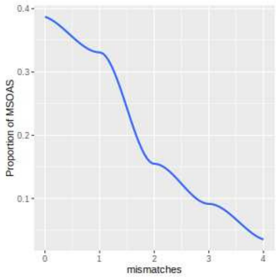
(a) Manchester

mismatch	frequency	%
0	25	17.6
1	35	24.6
2	46	32.4
3	22	15.4
4	14	10
total	142	100

(b) Null model randomised benchmark (Manchester)

mismatch	frequency	%
0	314	33.2
1	377	39.8
2	180	19
3	52	5.5
4	22	2.3
total	945	100

(c) London



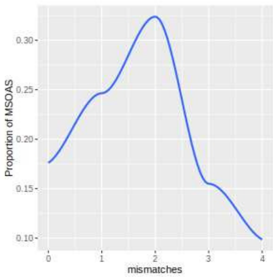


Table 5.2: Frequency distribution of the matching errors between actual and simulated data. $mismatch = 0$ means that an MSOA in one quintile of price variation in empiric data falls in the same quintile in the simulation. As a benchmark, Table (b) shows the outcome of a randomised null model, with MSOAs distributed randomly in quintiles.

anism at the core - are significant, and noteworthy. Pending further validation, this preliminary evaluation seems to suggest that the simple rules of the model might be able to capture, at least partially, the determinants of the motion of investment capital in an urban context.

In the up-scaled model the population of Manchester and London was also modelled after the actual population of the two cities with regards to income, ethnicity and religion. However the evolution of the social composition of the study areas was not monitored at this stage of development of the model.

5.3 Case study: the Pendleton(One) regeneration, Salford

In the following we employ a variant of the up-scaled model to investigate a policy issue of great local interest - namely, what might be the effect of a large scale regeneration programme ongoing, at the time of writing, in the Pendleton area of the City of Salford, Greater Manchester, in the North-West of England. For this exploration we add code to the model

Fig. 5.4: Pendleton in 2008

that mimics the planned intervention, we then compare two scenarios: one in which the intervention does take place as expected, and one in which it doesn't. This exercise is proposed to show the potential of our framework of giving valuable insight into the working of regeneration and inform a policy development process. In a sense it is a sophisticated kind of risk analysis - discovering some of the ways such an intervention could go wrong (or right) and thus enable those implementing the policy to better monitor the emergent consequences as the intervention develops.

PendletonOne[2] is the marketing name of a vast scale regeneration project ongoing in Salford. Pendleton lies 2 miles west of Manchester City Centre, has a population of 18,000 and is one of the areas with the highest indices deprivation in the country. The area was entirely (re)built in the 1960s and 70s, under the *Ellor Street Area Redevelopment Scheme* (Ellor street formerly traversed the length of Pendleton). The scheme was initiated as a move towards rational "civilised cities" for working people, designed to replace the squalor and deprivation of the Victorian era [54]. Under the scheme hundreds of streets of terraced

[2] `http://www.pendletonone.co.uk`

homes and factories were demolished and replaced by a modernist inspired housing estate of tower blocks, four storey slab blocks and low rise maisonettes, set in communal open spaces, in a combined civic and shopping centre (Figure 5.4) . The adjacent roads were brought to motorway standards, following recommendations from Colin Buchanan's influential report, *Traffic in Towns*, published in 1963 [21], which, as implemented, irreparably blighted a number of Britain's city centres. In the subsequent 50 years Pendleton experienced the fate of many modernist housing estates around Britain. The vision and optimism of the initial plan were never fully implemented from the onset, then a mixture of neglect, disinvestment, the accumulation of social disadvantage gained the area a profoundly bad reputation. In a historic perspective, the *typicality* of Pendleton is striking. Prior to 1960 the Ellor street/Hanky Park area epitomised *the classic slum*, an archetype fixed in the popular imagination by plays like *Love On the Dole*, by Salfordian Walter Greenwood, and songs like *Dirty Old Town* by Ewan MacColl, also inspired by this very area of Salford. Post-1970 Pendleton is also a type: this time of the post-war modernist estate, examples of which are to be found in every British city and town: Sheffield's Park Hill, Glasgow's Red Road come to mind, also currently interested by radical redevelopment plans.

Pendleton is adjacent to and Salford Quays and MediaCityUK - the media citadel built in the 2000s on the site of the old Manchester Docks (which, despite the name, lied in Salford) - home to the BBC, ITV and other major TV studios. Salford Quays was the successful outcome of monumental private investment (on formerly public land): apart from TV studios the area comprises of hundreds of high end apartments and canal side houses. Figure 5.6 shows Pendleton (the green area in figure b, pictured in red in figure a, as is predominantly social housing) and Salford Quays (the relatively large white area immediately to the south) side by side. This is an interesting case of a low-price area sitting next to a high-price one: an area where investment capital would probably flow to, in order to close the price gap. If it wasn't for a small problem: Pendleton is predominantly social housing (98%, as of 2008). And Social Housing is, by definition, a no-go area for capital. A regeneration programme that took place between 2009 and 2012, together with a number of Right-to-Buy acquisitions reduced the social housing share to 70%. However, despite these, the area failed to attract the necessary private investments and sits in bad conditions, as Jeffrey argues in his analysis of the socioeconomic situation of Pendleton in the wake of the 2011 riots [53]. The £400m redevelopment plans under way involve - again, like in the 1960s - extensive demolitions which will radically change the face of the area for the second iteration of *clearances* in less than 50 years, along with refurbishment of existing dwellings and building of new housing. The new builds expected to complete by 2018 range from a price of £115,000 to £155,000, as per the marketing website. Crucially, all the new development will be privately owned, further reducing the share of social housing in the area.

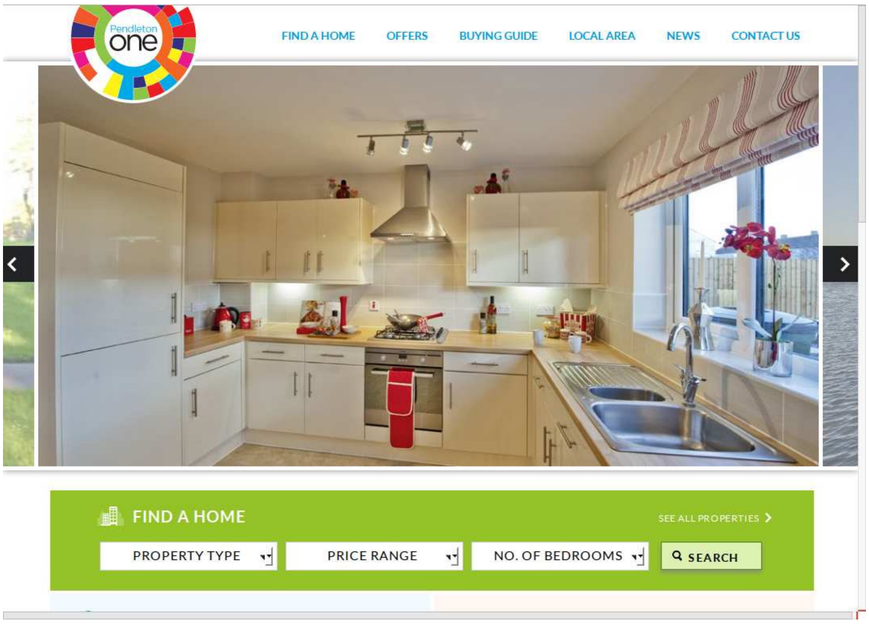


Fig. 5.5: PendletonOne Marketing site

In the following we report on a number of model runs using a variant of the up-scaled model, to try an assessment of what the possible outcomes of such an intervention could be in 10 years time. Specifically we ask whether the price levels of the study area will substantially increase, if investment brought in by the public purse will attract further development, and in what ways the social composition of the area will change. As mentioned we model two alternative situations: one in which the regeneration does not take place, and one in which the proposed intervention goes as planned. For each situation we test three levels of "capital" (Table 5.3) modelling three alternative and plausible economic scenarios.

Regeneration		Capital		
True	False	0.02	0.04	0.06

Table 5.3: Simulating the regeneration of Pendleton

5.3.1 GIS model and data sources

We employed the GIS model of the Manchester urban area presented in 3.4 and 5.2.2, which comprises of vector data on house prices, average household income, ethnicity and religion of the inhabitants. The study area covered by the PendletonOne regeneration is marked in green in Figure 5.6 and consists of 20 modelled locations. The initial population is of 4300 agents, with an income derived from the census and a cultural string of 10 dimensions, the first two of which map ethnicity and religion derived from the 2011 census. The first two features are fixed and the remaining eight are susceptible to change as a consequence of interaction with neighbours, as in the abstract model. We also assume a rudimentary “credit” system: agents are assumed to be able to acquire properties costing up to 6 times their annual income, although this parameter will have to be explored further, especially in the light of the government encouraging the substantial expansion of credit to new homeowners.

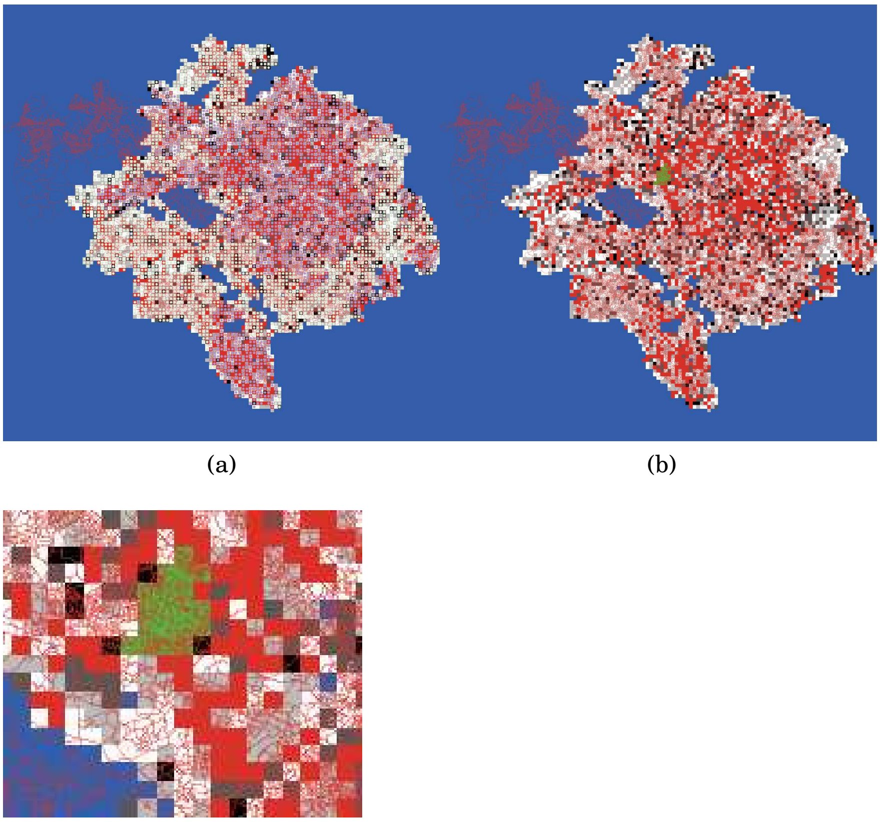
5.3.2 Results

Let us stress that being able to represent the whole city is crucial to model the assumptions of the RGT: capital will flow where it is profitable, and in our model, as in reality, Pendleton is in competition with the rest of Manchester to attract investment. We modelled the regeneration process by replacing 50% of the existing dwellings with restored housing (i.e. housing with condition $m = 0.95$) and a price range determined stochastically in the range prospected by the developer (115,000 - 155,000 GBP). The regeneration takes place between time steps 24 and 48, we then monitor the evolution of prices for the subsequent 20 years (480 time steps) in the PendletonOne area and the surrounding locations in radius 10. We compare the evolution of the price structure in the case of regeneration taking place and no regeneration happening at all and we test three levels of capital ($K = 0.02$, $K = 0.04$ and $K = 0.06$).

As Figure 5.7 shows, if no regeneration were to happen, prices in Pendleton would decline as investment would never reach the area for any of the levels of capital tested. In the case of $K = 0.06$, after about 13 years prices would rise in the area surrounding Pendleton, sign that for that level of investment, it would take more than 10 years before investing around Pendleton will be profitable. In Figure 5.8 we see the effects of regeneration for the same three levels of capital. In this case the outcomes differ according to the level of capital flowing into the city.

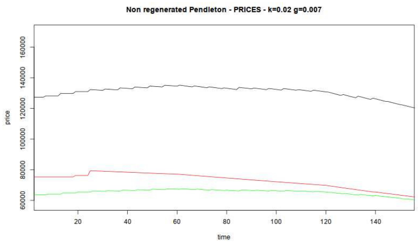
In Figure 5.9 we take a look at the income levels of the study area. In the regeneration case, gentrification can be spotted, as the higher prices drive out some of the original population that has the lowest median income in Greater Manchester.

It is worth noting that, while our assumed 6-times-the-income credit limit may be too restrictive or unrealistic, gentrification is often a byproduct of state sponsored regeneration programmes, especially in the UK and

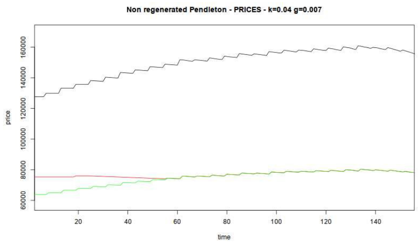


(a) (b) (c)

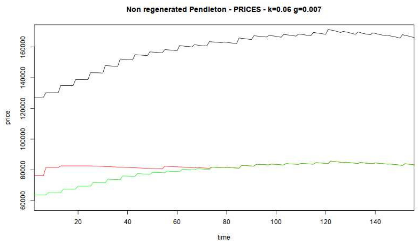
Fig. 5.6: The Manchester urban area represented in Netlogo. The color of the locations represents their maintenance conditions, as in the abstract model. Red patches represent social housing areas. The circles in (a) represent households, coloured according to their income levels: violet represents a below average income, green above average. The green area in (b) is the study area of PendletonOne. Notice how Pendleton lies in close proximity of a large white area: MediaCityUK/Salford Quays, an area of high maintenance/high price to its south (c).



(a) $K = 0.02$



(b) $K = 0.04$

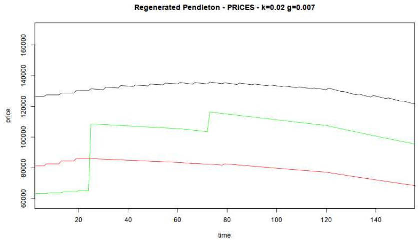


(c) $K = 0.06$

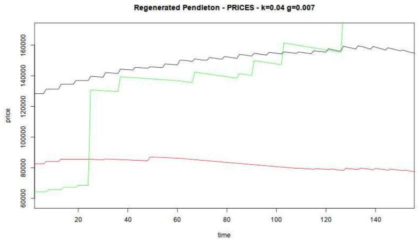
Fig. 5.7: Median price in the entire Manchester urban area (black), PendletonOne (green), and PendletonOne proximity (red) in case of no regeneration taking place for three levels of capital. In absence of regeneration the amount of capital that flows into the city is irrelevant to Pendleton and its surrounding area. The profitability of these parts is too low, compared to other parts of the city, to attract any investment.

in case of extensive demolition, as in Pendleton. The demolished properties are generally forcibly bought from the owners via a legal instrument called Compulsory Purchase Order for a price set by the local authority. Once the regeneration is completed, previous owners may find that no property is available in the local area for the amount they received and therefore, in order to stay in the neighbourhood, have to take up debt and many choose to move elsewhere. It is the case of many regenerations in London, notably the Elephant and Castle and, lately, the Heygate Estate, a blatant case of "social cleansing," according to many[3]. There is evidence that this phenomenon of government-driven gentrification is taking place in Pendleton as well, as Chris Allen points out [1].

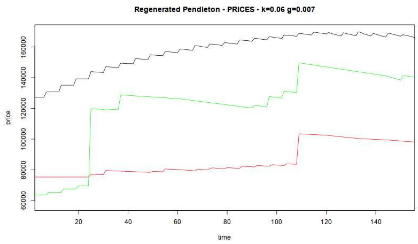
[3] `https://insidecroydon.com/2016/10/03/architects-plan-protest`



(a) k=0.02



(b) k=0.04

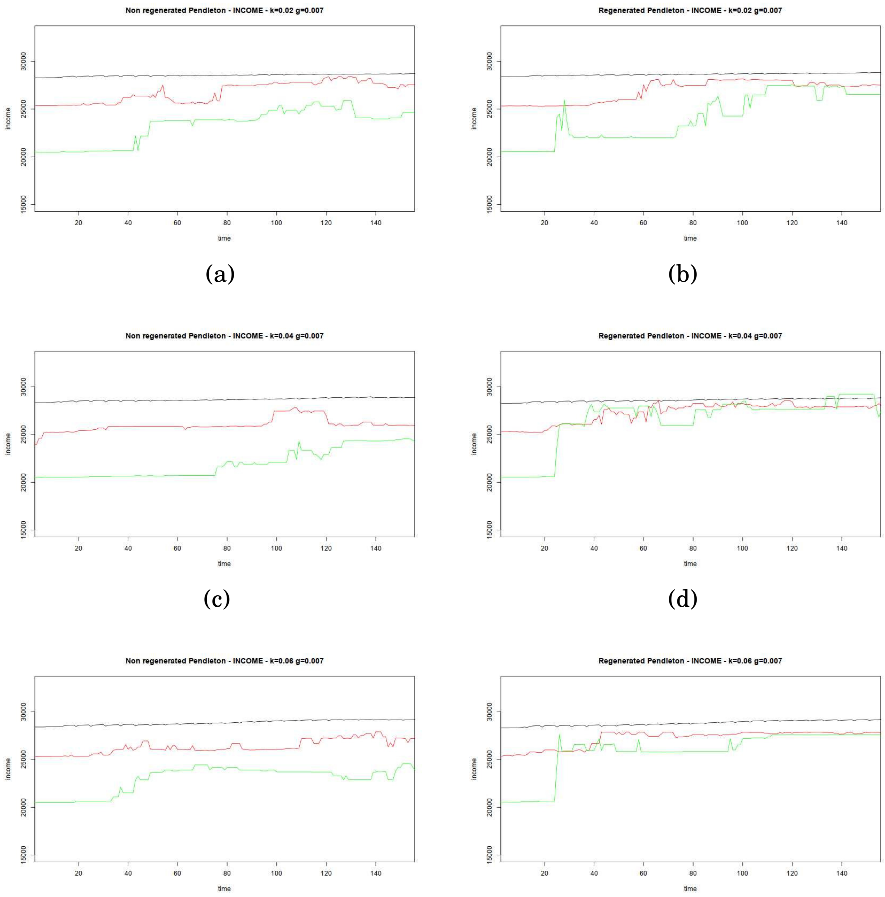


(c) k=0.06

Fig. 5.8: Median price in Manchester (black), PendletonOne (green), and PendletonOne proximity (red) for three levels of capital, with regeneration taking place at step 24. At $K = 0.02$ all prices decline and the regeneration has no long term effect. A level of$K = 0.04$ grants higher prices for a longer term, but has no effect on the area around Pendleton;$K = 0.06$ sustains high prices in PendletonOne and triggers investment in the surrounding area as well.

5.4 Conclusions and summary

The up-scaling of the RGT model was our attempt at bringing the theoretical assumptions of Critical Geography into the real world (i.e. in a slightly less stylised representation of the real world), and test the basic tenets of the Rent-Gap theory in a more data-driven fashion. Bearing in mind the multiple limitations of this model, detailed in Section 3.4.2, the results were rather encouraging. We based the validation of the model on two UK urban areas, Manchester and London. In both cases the model was initialised with the house price structure of these cities at the year 2001; then the variations in the price structure resulting from a 156 month run of the model were compared with the actual variations occurred in the period 2001-2015 (data from the Land Registry). The comparison between the modelled and observed variations of prices indicate that the basic logic implemented in the model was capable of reproducing



(a) (b)

(c) (d)

(e) (f)

Fig. 5.9: Median income in Manchester, PendletonOne and proximal area for three levels of capital in case of no regeneration taking place (a,c,e) and with regeneration taking place (b,d,f)

the target phenomenon to an **interesting** degree of accuracy. A significance test against a null-model was also performed, and it confirms this claim.

We then explored the usability of the up-scaled model as a perspective planning and policy evaluation tool. We modelled a real-world regeneration programme in its forecasted impact on the house price structure and social housing provision, and generated a range of hypotheses on the possible long-term outcomes of the programme on the social composition and economic development of the area. This is the first step towards the implementation of the model as a planning policy aide tool. Including tenure and a more realistically designed population would allow the model to produce more robust results, and generate hypotheses on further aspects of the phenomenon: the possible trajectories of those expelled by the area would be an extremely interesting and useful area into which enquire, for instance.

6

Conclusions

The main aim of this work has been to implement in code a particular socioeconomic hypotheses, the Rent Gap Theory, and propose it as a possible addition to the computational toolbox for the study of intra-urban dynamics. The idea upon which this work has been conceived is that the city is the product of agents of different nature, and the stress on bottom-up emergence of phenomena should not over-represent the role of individuals and households. A good model of urban dynamics should include agents of different magnitude and account for the mutation of the micro-level *scenario,* or context, that is often determined by processes unfolding independently, at the macro-level. The models that we built and presented here serve the theoretical purpose of clarifying and visualising certain mechanics that Critical Geographers had described only in theory, thus exploiting one prerogative of agent-based modelling: that of offering a different way of formulating theories. The encoded theory was capable of generating some of the most evident phenomena of the last century of urbanization - gentrification, segregation, spatial inequalities - all emerging purely as consequences of different levels and scopes of capital circulation, thus suggesting the centrality of (often neglected) structural factors in the emergence of urban dynamics. Our results offer an alternative view of these urban dynamics, not necessarily aimed at challenging their mainstream *demand-side* explanations, but suggesting that there may be more out there to look at, than the simple "consumer choice" approach, originating in the standard economic theory camp.

We have also tried to look at further implications of the original Rent Gap theory: some non immediately obvious consequences of capital circulation, i.e. those that affect the cultural make up of a city, have emerged in the models. Peculiar cultural identities emerged and vanished as transient and interstitial phenomena at the mercy of the superior will of an invisible, implacable entity that we called "Capital".

Also, a reliable tool for the evaluation of the social impact of urban regeneration policy, based on the core assumptions of the RGT, may not be too far away, once certain features will have been added to the model, namely density and tenure. We demonstrated the possible shape and applicability of such a tool in assessing the outcomes of an urban renewal programme.

We attempted a (quasi) real-world validation of the theory. Running an extended version of the model in a data rich GIS based space, we demonstrated that the simple mechanics implemented - despite several limitations and some inconsistencies - do seem to capture at least some of the processes that determine the flowing of investment capital in certain areas rather than others. However, the validation process was only partial, several parts of the model will have to be re-implemented in a less simplistic way, for it to be considered reliable. Still, in our view, this is a very promising aspect of the work. Further validation, a higher degree of descriptiveness are the obvious next steps for this branch of the model. Being able to accurately reproduce historical trends would open to the possibility of considering prediction as the possible next step of development. We can't completely reliably anticipate where in a city investment is likely to land yet, but we may be on a good path to get there in a not too distant future.

As a final remark, we wish to emphasise, once again, the role of *theory* in the humble intellectual endeavour described in these pages. In a cultural milieu that seems to be entertaining the idea that theory might be a nearly useless frill, and all the knowledge required could be extracted from raw *Data,* it is useful to stress that a theory - whether explicitly stated or not, whether knowingly or not - is always there. It is either produced on the spot, or unknowingly applied, every time that an interpretation of any kind of data is produced. Theory is a mean to go beyond simple generalisations of the evidence and to appreciate the deeper sense of phenomena. We tried to show that a somewhat counter-intuitive theory might explain phenomena in a way that would have been very difficult to conceive, just by looking at *Data.*

Acknowledgement. I wish to thank my supervisory team, Prof. Bruce Edmonds and Prof. Alison Heppenstall, for their mentoring, the stimulating discussions and, in particular, the great resilience and enviable *cold blood* that they displayed in dealing with me :-) I was given invaluable support and the greatest intellectual freedom. I hope to have made the most (or nearly the most, or at least something...) of it.

I am also thankful to past and present students, members, associates, visitors and passers-by of the Centre for Policy Modelling - brilliant researchers with whom I had the privilege to exchange ideas: David Hales, Ruth Meyer, Claire Little, Emma Norling, Ali Abbas, Magnus Josefsson, Peter Wallis. Credit to Bruce for creating and fostering such an intellectually stimulating environment at the Centre.

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I will always fondly remember Rosaria Conte, who sadly passed away in 2016. It was her engaging teaching and passionate, enquiring mind that got me fascinated by this field.

—

This work is dedicated to Diego Maradona.

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7

Appendix - model code, variants, future extensions

7.1 Abstract model extension: sprawl as an emerging effect of the housing market

The current implementation of the model and all its variants assumes fixed city boundaries: no expansion is possible beyond the initially set city limits. While this isn't a particularly implausible assumption - think of green belts that act as nearly impenetrable outer boundaries of UK urban areas - it prevents *a priori* some dynamics from emerging.

Urban sprawl, in David Harvey's view, can be thought as a byproduct of capital surplus and both a cause and effect of the mass diffusion of the automobile. In this regard, it would be the perfect phenomenon to model under the assumptions of the RGT, and would be another area in which to test the efficacy of the theory. A simple extension to the model would be needed, allowing for expansion of the built environment beyond the initially defined boundaries.

7.2 Abstract model extension: towards an agent-based simulation of housing in urban Beirut

We leveraged on the abstract model (Section 3.3) as a lens to study the effect of sizeable refugee migration in a stylised model of a densely-populated Mediterranean city. Our exploratory work provides the foundation for calibration with real data, and offers a step towards a tool for policy makers asking what-if questions about the urban environment in the context of migration. Specifically, we grounded our work in the city of Beirut, Lebanon. The densely-populated city is the capital of a middle-income country which has experienced a refugee influx of 50% of its population in the last 3-4 years, according to estimates. We expanded our ABM to model ethnic and religious profiles, *ownership*, and varying immigration and emigration rates. By means of an abstracted model of the city, we explored the outcomes of the refugee influx on various economic and social indicators .

This work was published in the proceedings of the 1st Workshop on Agent based modelling of urban systems in 2017 [73].

7.3 Extensions to the up-scaled model

The up-scaled model is very promising in its ability to identify the areas of a city where investment is likely to land. Even in its current stylised, and to some extent *incomplete,* form - as shown in Chapter 5 - the model seems to capture at least some of the dynamics involved in the investment cycles. However, it is unequivocal that more detail has to be added in order for it to be usable as a robust theoretical and possibly practical planning-aid tool. The limitations and shortcomings of the up-scaled model have been discussed in Section 3.4.2. A new version including a more sophisticated implementation of tenure and the inclusion of population density is currently being developed.

7.4 Model source code

All the source code for the two models and their variants, including GIS datasets and other accompanying material, is available under a Free (Libre) Software license agreement in the author's GitHub repository - `https://github.com/harrykipper/gentaxelling`. The full source code of the abstract model follows.

List of Figures

List of Tables

```
extensions [table]

globals [immigration districts file-name-pop file-name-entropy file-name-prices
file-name-income file-name-world file-name-allured version save-directory
  allured-districts firstallure declining neighbourhoods-table  ;; compiles a list
of neighbouhoods at start for quick lookup when running
  disp-freq ;; how many ticks between updates of entropy graph
  disp? ;; whether entropy graph should be displayed this tick
  city-allure
  av-income sd-income sd-income+ sd-income- occupation-rate gentrified-districts
downfiltered-districts
  recolonisation degentrification recreation regentrification
  housing-waiting-list file-name-donut
]

breed [citizens citizen]
breed [people person]
links-own [time]
turtles-own [mobility-propensity months-here birthday culture income dissonance
place-changes time-in-a-slum]
patches-own [ref condition price centre? dist local-dist premium price-gap months-
empty neighbourhood allure social? last-renovated]

to setup
  clear-all
  set version "0.2.16"
  set save-directory "~/results/"
  set disp-freq 5
  set disp? false
  set firstallure 0
  set allured-districts table:make
  set gentrified-districts table:make
  set downfiltered-districts table:make
  set housing-waiting-list table:make
  set declining []
  set recolonisation []
  set degentrification []
  set regentrification []
  set recreation []
  set city-allure n-values traits ["x"]
  ifelse enable-culture [
    set Mixing? true
    set PULL? true
    set PUSH? true
    set strong-neighbourhood? true
  ]
  [
    set Mixing? false
    set PULL? false
    set PUSH? False
    set strong-neighbourhood? false
    ]
  if Record? [movie-cancel]
  ;set allured-districts []
  ask patches
    [ set pcolor white
      set social? false
      set condition random-float 1
      create-price
      set months-empty 0
      set allure []
      set-neighbourhood
      ;set centreness 0.00001
     ; if areamax? [set premium 1]
    ]
  set districts remove-duplicates [neighbourhood] of patches

  set neighbourhoods-table table:from-list map [list ? (patches with
```

```
[neighbourhood = ?])] districts

  set-centres-and-distances
  ask patches [
    color-patches
    ;set-last-renovated
    ]
    create-people N-Agents * 10 [
      ;set size 0.01
      set size 0.5
      set birthday 0
      create-culture
      reset-mobility-propensity
      set hidden? true
    ]
    set-default-shape turtles "circle"
    create-economic-status
    allocate-agents
  reset-ticks
  if Record? [movie-start "~/gentaxelling.mov"]
  if write-csv? [prepare-data-save]
end

to create-price   ;; Price dependant on condition + location. We need to look into
this.
  set price condition + 0.1
  ;if neighbourhood = "cbd" [set price price * 1.30]
  if price > 1 [set price 1]
end

to set-centres-and-distances
  foreach districts [
    let x (([pxcor] of max-one-of patches with [neighbourhood = ?] [pxcor] -
[pxcor] of min-one-of patches with [neighbourhood = ?] [pxcor]) / 2) + [pxcor] of
min-one-of patches with [neighbourhood = ?] [pxcor]
    let y (([pycor] of max-one-of patches with [neighbourhood = ?] [pycor] -
[pycor] of min-one-of patches with [neighbourhood = ?] [pycor]) / 2) + [pycor] of
min-one-of patches with [neighbourhood = ?] [pycor]
    ask patch x y [
      if neighbourhood = ? [
        set centre? true
        set pcolor blue
      ]
    ]
  ]
  ask patches [
    let centre min-one-of patches with [centre? = true] [distance myself]  ;;
policentric city
    set local-dist distance centre
    set dist distancexy 0 0
    if kind = "policentric" [set dist local-dist]
    if kind = "no centres"  [set dist 1]
  ]
end

to set-neighbourhood
  if pxcor >= -10 and pxcor < -2 and pycor > 2 and pycor <= 10 [set neighbourhood
"nw"]
  if pxcor <= 10 and pxcor > 2 and pycor > 2 and pycor <= 10 [set neighbourhood
"ne"]
  if pxcor >= -2 and pxcor <= 2 and pycor >= -2 and pycor <= 2 [
    set neighbourhood "c"
    ;set plabel "CBD"
  ]
  if pxcor >= -10 and pxcor < -2 and pycor < -2 and pycor >= -10 [set
neighbourhood "sw"]
  if pxcor >= -10 and pxcor <= -3 and pycor > -4 and pycor < 4 [set neighbourhood
"w"]
```

```
  if pxcor <= 10 and pxcor > 2 and pycor < -2 and pycor >= -10 [set neighbourhood
"se"]
  if pxcor <= 10 and pxcor >= 3 and pycor > -4 and pycor < 4 [set neighbourhood
"e"]
  if pxcor >= -3 and pxcor <= 3 and pycor < -2 and pycor >= -10 [set neighbourhood
"s"]
  if pxcor >= -3 and pxcor <= 3 and pycor > 2 and pycor <= 10 [set neighbourhood
"n"]
end


to create-culture
  set culture n-values traits [random values]
end

to create-economic-status
  ask people [set income random-float 0.90]
  if random-income? = false
  [create-skewed-economic-status]
end

to allocate-agents
  while [count citizens < N-Agents] [
    ask one-of people [
      if any? patches with [count citizens-here = 0 and price <= [income] of
myself]
       [
         move-to one-of patches with [count citizens-here = 0 and price <=
[income] of myself ]
         set breed citizens
         set hidden? false
         color-agent
         ]
       set months-here 0
    ]
  ]
end

to reset-mobility-propensity
  set mobility-propensity (random-float prob-move) + 0.01
end

to create-skewed-economic-status
  ;;  adjust one up and one down each time since this method changes the mean -
Not SURE this is an improvement!
  let thresh 0.05
  let chng 0.8
  let chng-abs 0
  let med 0
  if init-gini - gini people > thresh [
    while [init-gini - gini people > thresh] [
      set med mean ([income] of people)
      ask one-of people with [income > med] [
        set chng-abs chng * (income - med)
        set income income + chng-abs
      ]
      ask one-of people with [income < med] [
        set income max list 0 income - chng-abs
      ]
      show (word med " " gini people)
    ]
  ]
  if gini people - init-gini > thresh
  [ while [gini people - init-gini > thresh] [
      set med mean ([income] of people)
      ask one-of people with [income < med] [
        set chng-abs chng * (med - income)
        set income income + chng-abs
```

```
      ]
      ask one-of people with [income > med] [set income max list 0 income - chng-
abs]
      show (word med " " gini people)
    ]
  ]
  ask turtles with [income > 1][set income 1]
end

to-report gini [group]
  let sorted-wealths sort [income] of group
  let total-wealth sum sorted-wealths
  let wealth-sum-so-far 0
  let index 0
  let gini-index-reserve 0
  let lorenz-points []
  repeat count group [
    set wealth-sum-so-far (wealth-sum-so-far + item index sorted-wealths)
    set lorenz-points lput ((wealth-sum-so-far / total-wealth) * 100) lorenz-points
    set index (index + 1)
    set gini-index-reserve gini-index-reserve + (index / count group) - (wealth-
sum-so-far / total-wealth)
  ]
  report (gini-index-reserve / count group) / 0.5
end

to-report occupancy [place]
  let total patches with [neighbourhood = place]
  let occupied count total with [count citizens-here > 0]
  report occupied / count total
end

to color-patches
  if condition >= 0.75 [set pcolor white]
  if condition < 0.75 and condition > 0.50 [set pcolor grey + 2]
  if condition <= 0.50 and condition > 0.25 [set pcolor grey - 2]
  if condition <= 0.25 [set pcolor black]
  if social? [set pcolor red]
end

to set-last-renovated
  if condition <= 0.15 [set last-renovated 120 + random 120]
  if condition > 0.15 and condition <= 0.25 [set last-renovated 60 + random 120]
  if condition > 0.25 and condition <= 0.5 [set last-renovated 60 + random 60]
  if condition > 0.5 and condition <= 0.75 [set last-renovated 24 + random 60]
  if condition > 0.75 [set last-renovated random 48]
end



to determine-phenomenon [place]
  ifelse median [income] of citizens-on patches with [neighbourhood = place] >
item 0 table:get allured-districts place
  [
    table:put gentrified-districts place (list median [income] of citizens-on
patches with [neighbourhood = place] median [price] of patches with [neighbourhood
= place] occupancy place)
    show word "Here is a gentrified neighbourhood: " place
    if write-csv? [export-view (word save-directory "/pics/" "GENTRIFIED_DISTRICT
-" "K" Kapital "-t" ticks "-" place ".png")]
    ]
  [
    table:put downfiltered-districts place (list median [income] of citizens-on
patches with [neighbourhood = place] median [price] of patches with [neighbourhood
= place] occupancy place)
    show word "Here is a downfiltered neighbourhood: " place
    if write-csv? [export-view (word save-directory "/pics/"
"DOWNFILTERED_DISTRICT -" "K" Kapital "-t" ticks "-" place ".png")]
```

```
    ]
end

to determine-super-phenomenon [district case]  ;; when a place lost than regained
uniformity. What's happening???
  ifelse case = 0  [   ;; in this case originally gentrification dissolved
uniformity
    ifelse median [income] of citizens-on patches with [neighbourhood = district]
>= (item 0 table:get gentrified-districts district - 0.1) and median [price] of
patches with [neighbourhood = district] >= (item 1 table:get gentrified-districts
district - 0.1)
    [
      show word "Here is a recolonised neighbourhood: " district
      if not member? district recolonisation [set recolonisation fput district
recolonisation]
      ;set recolonisation recolonisation + 1
      if write-csv? [export-view (word save-directory "/pics/"
"RECOLONISED_DISTRICT -" "K" Kapital "-t" ticks "-" district ".png")]
      ]
    [
      if not member? district degentrification [set degentrification fput district
degentrification]
      show word "Here is a DEGENTRIFIED neighbourhood: " district
      ;set degentrification degentrification + 1
      ]
  ] [ ; here originally downfiltering dissolved uniformity
  ifelse mean [income] of citizens-on patches with [neighbourhood = district] <=
(item 0 table:get downfiltered-districts district + 0.1)
  [set recreation fput district recreation]
  [set regentrification fput district regentrification]
  ]
end

to go
  ;if fixed-premium? = false [set-premia]
  ifelse ticks mod disp-freq = 0 [set disp? true] [set disp? false]
  ask patches [
    ifelse have-demand-premium [
      ifelse occupancy neighbourhood >= 0.8   ;; NON DEVE ESSERE SOLO
NEIGHBOURHOOD !!!
      [set premium 1 + renovation-premium]
      [ifelse occupancy neighbourhood >= 0.5
        [set premium 1 + random-float renovation-premium]
        [set premium 1 + random-float (renovation-premium * 0.8)]
      ]
    ] [set premium 1 + renovation-premium]
    if enable-economy? [
      if gaps = "mean" [set-gaps-mean]
      if gaps = "max" [set-gaps-max]
      if gaps = "unified"  [set-gaps-unified]
      if gaps = "new"  [set-gaps-new]
      decay
      reconsider-price
    ]
    update-emptiness
    ;update-centreness
  ]
  if ticks > 0 and (ticks = 24 or ticks mod 60 = 0) [
    set-city-allure
    foreach districts [
      if occupancy ? > 0.3 [set-allure ?]]
    ]
    ;if ticks < 1000 and any? patches with [allure = 0] [check-new-allure]
  ;if ticks mod 24 = 0 and table:length allured-districts > 0 [check-existing-
allure]
  update-links
  update-dissonance
  update-propensity
```

```
  if Mixing? [interact]
  ask citizens [
    set months-here months-here + 1
    if decide-moving [seek-place]
    ; set size 0.01 * months-here
    ; if size >= 1.4 [set size 1.4]
  ]
  if ticks > 0 and ticks mod 6 = 0 [
    if enable-economy? [do-business]
    if inmigration [inmigrate]
    if (any? patches with [social? and not any? citizens-here]) and (table:length
housing-waiting-list > 0) [assign-social-housing]
    if any? patches with [social?][check-social-residents]
  ]
  ask patches [color-patches]
  ;cluster-cultures
  ;update-vacancy-rates
  set av-income mean [income] of citizens
  set sd-income standard-deviation [income] of citizens
  set sd-income+ standard-deviation [income] of citizens with [income >= av-income]
  set sd-income- standard-deviation [income] of citizens with [income <= av-income]
  set occupation-rate count patches with [any? citizens-here] / count patches
  check-prices
  if Record? [movie-grab-view]
  tick
  if (ticks mod 12 = 0 or ticks = 1400) and write-csv? [save-data]
  if paperstuff? [
    if ticks = 300 or ticks = 600 or ticks = 900 or ticks = 1400 [export-view
(word save-directory Kapital "-t" ticks ".png")]
  ]
  if ticks = 1400 [
    if paperstuff? [export-plot "Mean prices by neighbourhood" (word save-
directory kapital)]
    if Record? [movie-close]
    stop
  ]
end

to check-social-residents
  ask citizens-on patches with [social?][
    if months-here >= max-time-in-social-housing * 12 [seek-place]
  ]
end

to assign-social-housing
  repeat count patches with [social? and not any? citizens-here] [
    let everybody []
    foreach table:keys housing-waiting-list [set everybody lput turtle ? everybody]
    let candidates sublist everybody 0 4
    let housedperson min-one-of turtle-set candidates [income]
    let locality table:get housing-waiting-list [who] of housedperson
    table:remove housing-waiting-list [who] of housedperson
    ifelse locality != "" and any? patches with [social? and not any? citizens-
here and neighbourhood = locality]
    [move-to-social-housing housedperson locality]
    [move-to-social-housing housedperson ""]
  ]
end

to move-to-social-housing [agent area]
  ask agent [
      set breed citizens
      set months-here 0
      set hidden? false
      ifelse area = ""
      [move-to one-of patches with [social? and not any? citizens-here]]
      [move-to one-of patches with [social? and not any? citizens-here and
neighbourhood = area]]
```

```
  ]
end

to check-prices
  foreach districts [
    ifelse member? ? declining
    [if median [price] of patches with [neighbourhood = ?] >= 0.25 [set declining
remove ? declining] ]
    [if median [price] of patches with [neighbourhood = ?] < 0.25 [set declining
fput ? declining] ]
    ]
end

to mutate-off
  ask one-of citizens [
    set culture replace-item (random traits) culture (random values)
    ]
end

to mutate
  let where [neighbourhood] of patch-here
  let trait (random traits)
  let most one-of modes [item trait culture] of citizens-on patches with
[neighbourhood = where]
  set culture replace-item trait culture most
end

to do-business
  let howmany (Kapital * count patches) / 2
  let goodgap patches with [price-gap >= (price * profit-threshold) and not social?
]; and condition <= 0.75];
  ; let goodgap patches with [price-gap >= profit-threshold]; and condition <=
0.75];
  if count goodgap < howmany [set howmany count goodgap]
  ask max-n-of howmany goodgap [price-gap] [renovate]
end

to inmigrate
  let howmany 1 + ((count citizens * immigration-rate) / 2)
  ask n-of howmany people [
    let myprice income
    if any? patches with [price <= myprice and not any? citizens-here and not
social?]
    [
      let whoami who
      ; set income random-float 1
      set breed citizens
      set hidden? false
      seek-place
      ifelse table:has-key? housing-waiting-list whoami   ;; if the person is from
the housing list we take him away
      [table:remove housing-waiting-list whoami]
      [                                                    ;; if not he becomes a
citizen ;-)
        set birthday ticks
        create-culture
        color-agent
        reset-mobility-propensity
      ]
    ]
  ]
end

to color-agent
  if income >= 0.80 [set color green]
  if income < 0.80 and income > 0.5 [set color green + 4]
  if income <= 0.5 and income >= 0.25 [set color violet + 2]
  if income < 0.25 [set color violet - 1]
```

```
end

to-report decide-moving
  if ([price] of patch-here > income and not [social?] of patch-here) or (random-
float 1 < mobility-propensity) [
    set place-changes place-changes + 1
    report true
  ]
  report false
end

to enter-housing-list [agent place]
  ;; set housing-waiting-list lput (list(agent)(place)) housing-waiting-list
  table:put housing-waiting-list [who] of agent place
  ask agent [
    set breed people
    set hidden? true
    ]
end

to leave-city
  ask my-links [die]
  set breed people
  set hidden? true
end

to renovate
  set price price + price-gap
  if price >= 1 [set price 0.98]
  set condition 0.95
  set last-renovated ticks
end

to decay
   ; if state = "RENTED" [set decay-factor depreciation * 2]  ;; We don't have
this yet
   let depr monthly-decay
   let time ticks - last-renovated
   if time < 48 [set depr 0]
   if time >= 48 and time <= 60 [set depr depr / 2]
   if time >= 120 and time <= 240 [set depr depr * 2]
   if not any? citizens-here [set depr depr * 1.20]
   ifelse condition - depr <= 0
      [set condition 0]
      [set condition condition - depr]
   if condition <= 0.2 and social? [set condition 0.55]
end

to reconsider-price
  ifelse social?
  [set price (mean [price] of patches) / 2]
  [
    let depr yearly-depreciation / 12
    let time ticks - last-renovated
    if time <= 48 [set depr 0]
    if time > 48 and time <= 60 [set depr depr / 2]
    if time >= 120 and time <= 240 [set depr depr * 2]
    if months-empty > tolerable-vacancy [set depr depr * 2]
    ifelse price - (price * depr) <= 0
      [set price 0.01]
      [set price price - (price * depr)]
  ]
end

to update-emptiness
  ifelse count citizens-here = 0
  [set months-empty months-empty + 1]
  [set months-empty 0]
```

```
end

to update-links
 ask links [    ;; First we check existing links. If the agents are still
neighbours we reinforce the relationship, if not we weaken it.
    let stillclose false
    ask one-of both-ends [if neighbourhood = [neighbourhood] of other-end or
distance other-end <= 2 [
        set stillclose true] ]
    ifelse stillclose
    [if time < 12 [set time time + 1]]
    [
      set time time - 1
      if time <= 0 [die]
    ]
  ]
  ask citizens [  ;; Then we create new links for neighbours that still don't have
one (i.e. new neighbours)
    let myneighbours other citizens with [distance myself <= 2 and link-neighbor?
myself = false]
    let goodneighbours myneighbours with [(similarity self myself / traits) >=
similarity-for-friendship]
    ask goodneighbours [
      create-link-with myself [
        set time 1
        set hidden? true
      ]
    ]
  ]
end

to build-social-housing [howmany]
  let sofar 0
  let zerop min [price] of patches
  let zeroc min [condition] of patches
  let avg mean [price] of patches with [count citizens-here > 0]
  let firstsocial nobody
  let worst patches with [not any? citizens-here and price <= zerop and condition
<= zeroc]
  ifelse any? worst
  [set firstsocial min-one-of worst [price-gap]]
  [set firstsocial max-one-of patches [months-empty]]
  ask firstsocial [
    set social? true
    set price avg / 2
    set condition 0.95
    set sofar sofar + 1
    while [sofar < howmany] [
      ask one-of patches in-radius 4 with [not social?] [
        if not any? citizens-here [
          set social? true
          set price avg / 2
          set condition 0.95
          set sofar sofar + 1
        ]
      ]
    ]
  ]
end

to regenerate
;; Regeneration is intended in the anglo-saxon, "small state but lets-be-
compassionate-shall-we" way.
;; Money is put in the areas least desirable to investors (= those with the most
narrow price-gap)
;; that are also empty and in run-down condition. These areas are brought to the
maximum condition
;; and to the mean price of the city. The idea is to check whether this practice
```

```
can trigger further private investment.
  let zerop min [price] of patches
  let zeroc min [condition] of patches
  let avg mean [price] of patches with [count citizens-here > 0]
  let worst patches with [not any? citizens-here and price = zerop and condition =
zeroc]
  ask min-one-of worst [price-gap] [
    set price avg
    set condition 0.95
    ask neighbors with [not social?] [
      set price avg
      set condition 0.95
    ]
  ]
end

to update-dissonance
  ask citizens [
    ifelse [condition] of patch-here < 0.15
      [set time-in-a-slum time-in-a-slum + 1]
      [set time-in-a-slum 0]
    if PUSH? [
      if count citizens-on neighbors > 0 [
        let alltraits count citizens-on neighbors * traits
        let simil 0
        ask citizens-on neighbors [set simil simil + similarity self myself]
        ifelse (simil / alltraits) <= similarity-for-dissonance
        [set dissonance dissonance + 1]
        [set dissonance 0]
      ]
    ]
  ]
end

to update-propensity
  ask citizens [
    if time-in-a-slum = 0 and dissonance <= tolerable-dissonance [reset-mobility-
propensity]
    if ((time-in-a-slum > 12) and (income > ([price] of patch-here * 1.20)))
      or (income >= ((median [condition] of neighbors) * 1.50))
      [set mobility-propensity mobility-propensity * 1.50]
    if (dissonance > tolerable-dissonance) [
      set mobility-propensity mobility-propensity * 1.50
      if random-float 1 < 0.05 [mutate]
      ]
    if mobility-propensity > 1 [set mobility-propensity 1]
  ]
end

;; The idea here is that prolonged co-location leads to cultural mixing.
;; We need each household to keep track of how long they have been neighbours with
each other
to interact
  ask links with [time >= 12] [
    let a end1
    let c-a [culture] of a
    let b end2
    let c-b [culture] of b
    if c-a != c-b [
;;    if similarity a b < traits [
      let whichone random traits
      let i-a item whichone c-a
      let i-b item whichone c-b
      if i-a != i-b [
        ifelse random 1 = 0
          [ask b [set culture replace-item whichone culture i-a]]
          [ask a [set culture replace-item whichone culture i-b]]
      ]
```

```
    ]
  ]
end

to-report entropy [district]
  let common 0
  let thispeople citizens-on patches with [neighbourhood = district]
  let pairs (count thispeople * (count thispeople - 1)) / 2
  ask n-of (count thispeople / 2) thispeople [
    ask other thispeople [
      set common common + (similarity self myself / traits)
    ]
  ]
  report safe-division common pairs
end

to-report entropy-old [district]
  let common 0
  let thispeople citizens-on patches with [neighbourhood = district]
  let pairs (count thispeople * (count thispeople - 1)) / 2
  ask thispeople [
    ask other thispeople [
      set common common + (similarity self myself / traits)
    ]
  ]
  report safe-division (common / 2) pairs
end


;============ RESIDENTIAL LOCATION PROCESS =============================


;; When seeking a spot we consider vacant affordable places close to the origin
(cbd) and with a pleasant cultural mix.
;; This is in line with Jackson et al. 2008, although they have a Schelling-like
ethnic (not cultural) mix.
;; In this version agents only evaluate the CULTURAL ALLURE of a district, not the
STATUS.
;; If we are to finegrain the model we could also include status in the decision
process.

to seek-place
  ifelse PULL? and table:length allured-districts > 0
  [
    let where set-place
    ifelse where != "" [
      ifelse strong-neighbourhood?
      [relocate-to where]
      [weak-relocate-to where]
    ][relocate]
  ]
   [relocate]
end

to-report set-place
  let best_ftr 1
  let bestdistrict ""
  foreach table:keys allured-districts [
    let this_similarity similarity self one-of patches with [neighbourhood = ?]
    if this_similarity >= best_ftr [
      set best_ftr this_similarity
      set bestdistrict ?
      ]
    ]
  report bestdistrict
end

to relocate
```

```
  set months-here 0
  let baseline patches with [(count citizens-here = 0) and (condition > 0) and
(social? = false)]
  if enable-economy? [set baseline baseline with [(price <= [income] of myself)]]
  ifelse any? baseline [
    let testbed n-of 5 patches
;    let secondbest baseline with [(price <= [income] of myself) and (count
citizens-here = 0) and (condition >= (mean [condition] of testbed - (mean
[condition] of testbed * 0.15 )))]  ;; if we can't find a place we like then we
move to one we can afford
    let secondbest baseline with [(price <= [income] of myself) and (count
citizens-here = 0) and (condition >= 0.25)]  ;; if we can't find a place we like
then we move to one we can afford
    ifelse any? secondbest
    [move-to min-one-of secondbest [dist]]
    [move-to min-one-of baseline [dist]]
  ]
  [enter-housing-list self ""]
end

to relocate-to [place]
  set months-here 0
  let baseline patches with [(price <= [income] of myself) and (count citizens-
here = 0) and (condition > 0) and (social? = false)] ;Add to prevent people from
moving to decrepit loc:; and (condition > 0)
  ifelse any? baseline [
    ;let testbed n-of 5 patches
    ;let condi mean [condition] of testbed
    ;let ideal baseline with [(neighbourhood = place) and (condition >= (condi -
(condi * 0.15 )))]
    let ideal baseline with [(neighbourhood = place) and (condition > 0.25)]
    ifelse any? ideal
      [move-to min-one-of ideal [local-dist]]
      [
        let apex patches with [centre? = true and neighbourhood = place]
        let acceptable baseline with [condition >= 0.10]    ;;; change this:
acceptable condition should vary across agents
        let secondbest acceptable with [neighbourhood = place] ;; change this: if
nothing is available in place look at the edges
        ifelse any? secondbest
        [move-to min-one-of secondbest [local-dist]]
        [ifelse any? acceptable
          [move-to min-one-of acceptable [distance one-of apex]]
          [move-to min-one-of baseline [dist]]
        ]
     ]
  ]
  [enter-housing-list self place]
end

to weak-relocate-to [place]
    let ideal patches with [(price <= [income] of myself) and (count citizens-here
= 0) and (neighbourhood = place) and (condition >= (mean [condition] of patches -
(mean [condition] of patches * 0.15 )))]
    ifelse any? ideal
    [move-to min-one-of ideal [dist]]
    [ let testbed n-of 5 patches
      let secondbest patches with [(price <= [income] of myself) and (count
citizens-here = 0) and (condition >= (mean [condition] of testbed - (mean
[condition] of testbed * 0.15 )))]  ;; if we can't find a place we like then we
move to one we can afford
      ifelse any? secondbest
      [move-to min-one-of secondbest [dist]]
      [let thirdbest patches with [(price <= [income] of myself) and (count
citizens-here = 0)  ] ;; Uncomment the following to prevent people from moving in
decrepit locations ;and (condition > 0)
       ifelse any? thirdbest [move-to min-one-of thirdbest [dist]] [enter-housing-
list self place]  ;; if no place exists we leave the city.
```

```
      ]
    ]
end

; =============================== PRICE GAPS ====================================

to set-gaps-new   ;; Maximum of moore neighbourhood or district median
 let whichprice 0
 let neigh-price 0
 let area-price 0
 set neigh-price max [price] of neighbors
 set area-price median [price] of patches with [neighbourhood = [neighbourhood] of
myself] * premium
 ifelse neigh-price > area-price
 [set whichprice neigh-price]
 [set whichprice area-price]
 ifelse whichprice > price
 [ifelse any? citizens-here with [income < whichprice]     ; We anticipate whether
we will have to kick someone out...
    [set price-gap (whichprice - (price + resident-removal-cost))]              ;
The removal cost affects the profit prospect...
    [set price-gap (whichprice - price)]
  ]
  [set price-gap 0]
end

to set-gaps-unified  ;;
 let whichprice 0
 let localprice mean [price] of neighbors * (1 + renovation-premium)
 if count citizens-on neighbors / count neighbors >= 0.85 [set localprice max
[price] of neighbors * (1 + renovation-premium) ]
 ifelse occupancy neighbourhood >= 0.85
 [set whichprice max [price] of patches with [neighbourhood = [neighbourhood] of
myself] * (1 + renovation-premium)]
 [set whichprice mean [price] of patches with [neighbourhood = [neighbourhood] of
myself] * (1 + renovation-premium)]
 if localprice > whichprice [set whichprice localprice]
 ifelse whichprice > price
 [ifelse any? citizens-here with [income < whichprice]     ; We anticipate whether
we will have to kick someone out...
    [set price-gap (whichprice - (price + resident-removal-cost))]              ;
The removal cost affects the profit prospect...
    [set price-gap (whichprice - price)]
  ]
  [set price-gap 0]
end

to set-gaps-mean
 let whichprice 0
 let localprice mean [price] of neighbors * premium
 ;if count citizens-on neighbors / count neighbors >= 0.85 [set localprice max
[price] of neighbors * premium ]
 ;ifelse occupancy neighbourhood >= 0.85
 ;[set whichprice max [price] of patches with [neighbourhood = [neighbourhood] of
myself] * premium]
 set whichprice mean [price] of patches with [neighbourhood = [neighbourhood] of
myself] * premium
 if localprice > whichprice [set whichprice localprice]
 ifelse whichprice > price
 [ifelse any? citizens-here with [income < whichprice]     ; We anticipate whether
we will have to kick someone out...
    [set price-gap (whichprice - (price + resident-removal-cost))]              ;
The removal cost affects the profit prospect...
    [set price-gap (whichprice - price)]
  ]
  [set price-gap 0]
end
```

```
to set-gaps-max
 set premium 1.001
 let whichprice 0
 let localprice max [price] of neighbors * premium
 ;if count citizens-on neighbors / count neighbors >= 0.85 [set localprice max
[price] of neighbors * premium ]
 ;ifelse occupancy neighbourhood >= 0.85
 ;[set whichprice max [price] of patches with [neighbourhood = [neighbourhood] of
myself] * premium]
 set whichprice max [price] of patches with [neighbourhood = [neighbourhood] of
myself] * premium
 if localprice > whichprice [set whichprice localprice]
 ifelse whichprice > price
 [ifelse any? citizens-here with [income < whichprice]     ; We anticipate whether
we will have to kick someone out...
    [set price-gap (whichprice - (price + resident-removal-cost))]              ;
The removal cost affects the profit prospect...
    [set price-gap (whichprice - price)]
  ]
  [set price-gap 0]
end


; =================== ALLURE ====================================================

to-report update-city-culture
  let newallure n-values traits [0]
  let trt 0
  while [trt < traits] [
    let thistrait one-of modes [item trt culture] of citizens
    set newallure replace-item trt newallure thistrait
    set trt trt + 1
  ]
  report newallure
end

to set-city-allure
  let city-culture update-city-culture
  let pallure []
  let trait 0
  while [trait < traits] [
    set pallure lput ifelse-value (count citizens with
      [(item trait culture = item trait city-culture)] >= (count citizens * 0.3))
    [item trait city-culture] ["x"] pallure
    set trait trait + 1
    ]
  set city-allure pallure
end

to-report localculture [district]
  if any? citizens-on patches with [neighbourhood = district] [
    let people-here citizens-on patches with [neighbourhood = district]
    let newallure n-values traits [0]
    let trt 0
    while [trt < traits] [
      let thistrait one-of modes [item trt culture] of people-here
      set newallure replace-item trt newallure thistrait
      set trt trt + 1
    ]
    report newallure
   ; ask patches with [neighbourhood = district] [set pculture newallure]
  ]
end

to set-allure [place]
  let ppl citizens-on patches with [neighbourhood = place]
  let areaculture localculture place
  let pallure []
```

```
  let trait 0
  while [trait < traits] [
    set pallure lput ifelse-value
    (count ppl with [item trait culture = item trait areaculture] > count ppl *
0.3 and
      item trait areaculture != item trait city-allure and
      item trait city-allure != "x"
      )
    [item trait areaculture] ["x"] pallure
    set trait trait + 1
  ]
  let peculiar length filter [? != "x"] pallure
  set-current-plot "peculiarity"
  set-current-plot-pen place
  plotxy ticks peculiar
  ifelse peculiar > peculiarity-for-allure [
    ask patches with [neighbourhood = place] [set allure pallure]
    if not table:has-key? allured-districts place
    [table:put allured-districts place (list (median [income] of citizens-on
patches with [neighbourhood = place]) (median [price] of patches with
[neighbourhood = place]) (occupancy place) (ticks))]
  ]
  [if table:has-key? allured-districts place [
      let longevity ticks - item 3 table:get allured-districts place
      if longevity > 60 [table:remove allured-districts place]]
  ]
end

; =================== SUPPORTING ====================

to-report safe-division [a b]
  if a = 0 or b = 0 [report 0]
  report a / b
end

to-report similarity [a b]
  report similarity-of ([culture] of a) (ifelse-value is-turtle? b [[culture] of
b] [[allure] of b])
end

to-report similarity-of [ls1 ls2]                   ;;;;;; DA QUA DOBBIAMO
PRENDERE IL CODICE PER FARE IL NUOVO ENTROPY
  report length filter [?] (map [?1 = ?2] ls1 ls2)
end


; =================== SCENARIOS ===================================================

to scenario-1
end

to scenario-2
end

to scenario-3
end

to scenario-4
end

; =================== PLOTTING ====================================================

to plot-ent [dis]
  if disp? [repeat disp-freq [plot entropy dis]]
end

to-report medianincome [area]
  ifelse any? citizens-on patches with [neighbourhood = area] [
```

```
    report median [income] of citizens-on patches with [neighbourhood = area]
  ][report 0]
end

; ============================ DATA OUTPUT
==========================================

to prepare-data-save
  let run-number 0
  ;let maxmean "MEAN"
  let pull ""
  let mix ""
  ;if areamax? [set maxmean "MAX"]
  if PULL? [set pull "PULL"]
  if behaviorspace-run-number != 0 [set run-number behaviorspace-run-number]
  set file-name-entropy (word save-directory "gentax-" version "-ENTROPY-" pull "-
K" Kapital "-#" run-number ".csv")
  set file-name-pop (word save-directory "gentax-" version "-POPULATION-" pull "-
K" Kapital "-#" run-number ".csv")
  set file-name-prices (word save-directory "gentax-" version "-PRICES-" pull "-K"
Kapital "-#" run-number ".csv")
  set file-name-donut (word save-directory "gentax-" version "-DONUT-" pull "-K"
Kapital "-#" run-number ".csv")
  set file-name-income (word save-directory "gentax-" version "-INCOME-" pull "-K"
Kapital "-#" run-number ".csv")
  set file-name-allured (word save-directory "gentax-" version "-ALLURE.csv")
  ;file-delete file-name-entropy
  ;file-delete file-name-pop
  ;file-delete file-name-prices
  ;file-delete file-name-income
  file-open file-name-entropy
  file-write "ticks;"
  foreach districts [file-write (word ? ";")]
  file-print ""
  file-open file-name-pop
  file-write "ticks;"
  foreach districts [file-write (word ? ";")]
  file-print ""
  file-open file-name-prices
  file-write "ticks;"
  foreach districts [file-write (word ? ";")]
  file-print ""
  file-open file-name-income
  file-write "ticks;"
  foreach districts [file-write (word ? ";")]
  file-print ""
  file-open file-name-donut
  file-print "ticks;centre;semicentre;periphery"
  file-close-all
end

to save-data
  let run-number 0
  if behaviorspace-run-number != 0 [set run-number behaviorspace-run-number]
  file-open file-name-entropy
  file-write (word ticks ";")
  foreach districts [file-write (word entropy ? ";")]
  file-print " "
  file-open file-name-pop
  file-write (word ticks ";")
  foreach districts [file-write (word count citizens-on patches with
[neighbourhood = ?] ";")]
  file-print " "
  file-open file-name-prices
  file-write (word ticks ";")
  foreach districts [file-write (word mean [price] of patches with [neighbourhood
= ?] ";")]
  file-print " "
```

```
  file-open file-name-donut
  file-print (word ticks ";" median [income] of citizens-on patches with
[distancexy 0 0 < 4] ";" median [income] of citizens-on patches with [distancexy 0
0 >= 4 and dist < 8] ";" median [income] of citizens-on patches with [distancexy 0
0 >= 8])
  file-open file-name-income
  file-write (word ticks ";")
  foreach districts [file-write (word safe-division sum [income] of citizens-on
patches with [neighbourhood = ?] count citizens-on patches with [neighbourhood = ?
] ";")]
  file-print " "
;  if ticks = 1400 [
;    let current-allure 0
;    foreach districts [
;      if (entropy ? >= similarity-for-allure and occupancy ? > 0.3) [set current-
allure current-allure + 1]
;    ]
;    file-open file-name-allured
;    ; file-print (word "kapital;total;final;first-emerged;max-longevity;run-
number")
;    file-print (word Kapital ";" table:length allured-districts ";" current-
allure ";" firstallure ";" [al-longevity] of one-of patches with-max [al-
longevity] ";" run-number)
;  ]
  if Record? [movie-grab-view]
  ;[
   ; if ticks = 300 or ticks = 600 or ticks = 900 or ticks = 1200 or ticks = 1400 [
    ;  set file-name-world (word save-directory "gentax-" version "-world-k"
Kapital "-#" run-number "_" ticks ".png")
    ;  export-view file-name-world
   ; ]
  ;]
  file-close-all
end
```