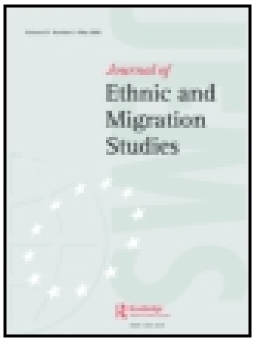

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Exploring the dynamics of neighbourhood ethnic segregation with agent-based modelling: an empirical application to Bradford, UK

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ABSTRACT

How individuals' residential moves translate into overall emergent segregation patterns remains a key challenge in neighbourhood ethnic segregation research. In this paper, we use agent-based modelling to explore this concern, focusing on the interactive role of ethnic and socio-economic homophilic preferences and socioeconomic housing constraints as determinants of residential choice. Specifically, we extend the classic Schelling model to a random utility discrete choice approach to simulate the relocation decisions of people. We model different weights for preferences for ethnic and socioeconomic similarity in neighbourhood composition over random relocations, in addition to housing constraints. We formalise how different combinations of these variables could replicate empirically observed ethnic segregation scenarios in Bradford, a substantially segregated local authority in the UK. We initialise our model with geo-referenced data from the 2011 Census and use various measures of segregation to describe our results. As in the original Schelling model, we find that even mild ethnic preferences alone would lead to unrealistic ethnic over-segregation in Bradford. However, we demonstrate that such process can be altered in favour of less ethnic segregation when agents' preferences for socioeconomic similarity are slightly stronger than their preferences for ethnic similarity. We discuss theoretical and policy contributions of our findings.

KEYWORDS

Agent-based modelling; homophilic preferences; housing constraints; neighbourhood ethnic segregation; Schelling

1. Introduction

What role do individuals' residential behaviour play in neighbourhood ethnic segregation? This question has been at the core of migration and urban studies research. Yet, the current answer to it is partial. Segregation research – especially the one conducted in the UK – has been dominated by studies on segregation levels (e.g. Catney 2018; Harris 2017; Simpson 2007), neighbourhood effects (e.g. Clark and Drinkwater

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2002; Zuccotti and Platt 2017), residential dynamics, and neighbourhood attainment (e.g. Coulter and Clark 2019; Zuccotti 2019). However, the link between micro-behaviours and emergent macro-phenomena have played a minor role in segregation research. In other words, there is limited understanding of how individuals' moves in space, mediated by their residential preferences and constraints (i.e. micro-behaviours), *translate* into the overall emergent segregation patterns that we observe (i.e. macro phenomena). Inspired by the field of analytical sociology – whose main aim is to understand what complex and intricated set of social processes and their interactions lead to emergent macro phenomena (Hedström and Bearman 2009; Manzo 2014) – our paper addresses this research gap through the case study of Bradford, UK. Specifically, we investigate what role individuals' residential moves, mediated by their ethnic and socioeconomic homophilic preferences and by socioeconomic housing constraints, play in the creation of Bradford's ethnic spatial structure. Both homophilic preferences and housing constraints are known to be key determinants of individuals' residential moves (Charles 2003; Krysan and Crowder 2017), and are therefore the focus of the present study.[1]

To achieve our goal, we use agent-based modelling (ABM). More specifically, we build on one of the earliest and most popular agent-based models: the Schelling (1969, 1971) model of segregation. The central intuition of ABM is that social order is build up from the unscripted actions of individual agents who constitute the social system and act in relation to others (Hedström and Bearman 2009, 19). In ABM, agents are (or can be) heterogeneous, autonomous, physically conditioned by space, socially embedded in a network, and guided by realistic rules of behaviour and decision processes. In contrast to other methods, ABM allows to define a rich and realistic set of micro specifications and deduce its high-level consequences (León-Medina 2017, 160). The Schelling model applies this idea to the study of spatial segregation. The model allows simulating characteristics and preferences of individuals (agents) and to formalise the appearance or development of spatial segregation as an aggregated *emergent* phenomenon of their interaction (Clark and Fossett 2008; Huang et al. 2014; Macy and Willer 2002). In its original version (Schelling 1969, 1971), the most important preference is the fraction of members of the own (ethnic) group that an individual would want in the neighbourhood (represented by the agent's *threshold*). People would stay in a neighbourhood if the fraction of in-group members does not fall below their threshold, and relocate elsewhere otherwise. The Schelling model demonstrates that even mild individuals' preferences (i.e. low thresholds) for co-ethnics can cause high levels or even full ethnic segregation through the cascade effects originating from individuals' relocation decisions (further details on this mechanism in the Online Annex).[2] A main lesson from this model is, therefore, that highly segregated societies do not necessarily stem from high levels of ethnic prejudice.

The Schelling model has been used mostly as a theoretical framework or to understand spatial dynamics in a more conceptual way. New computational developments (see Drouhot et al., 2022), and in particular the possibility to combine ABM interfaces (such as NetLogo) with empirical geo-referenced data (through GIS add-ins and shapefiles), allows implementing the Schelling model to the analysis of existing segregation dynamics, with real world data. We follow this approach in the present study, by combining the Schelling model with geo-referenced Census data (2011) on Bradford. More specifically, we extend the original version of the Schelling model of segregation to include both ethnic and socioeconomic preferences, as well as socioeconomic housing constraints, in modelling individual behaviour (see also Aldén, Hammarstedt, and Neuman 2015; Bruch 2014; Fossett 2006). The availability of empirical Census data on *both* ethnic and socioeconomic compositions of neighbourhoods allows us to do so. We implement a discrete choice version of the model (see also Bruch 2014): agents select whether to leave the current neighbourhood and which neighbourhood to move to using a utility function including the desired *threshold* for ethnic and socioeconomic similarity and *weights* for each dimension. The weights quantify how important each dimension is for individuals. Housing constraints are further incorporated to regulate where agents can move to, based on their socioeconomic characteristics.

Bradford, a half-million populated Local Authority (LA) in the north of England, is an interesting case study to explore these dynamics. First, Bradford has a relatively high share of non-white ethnic minorities, around one quarter of its population, and is also one of England's LAs with the highest neighbourhood ethnic segregation (Catney 2018; Lan, Kandt, and Longley 2020; Zuccotti 2021). Second, Bradford is one of the most deprived LAs in England:[3] once an attractive location for migrants and their families in the post-war era, it later became an area of industrial decay, with increasing unemployment and poverty. Third, and most importantly, Bradford has been the target of effervescent debates about neighbourhood ethic segregation, following the 2001 riots. These riots emerged as a consequence of the strong spatial association between ethnic concentration and neighbourhood deprivation, housing discrimination, and increasing antagonism between ethnic minorities and White British individuals. Back then, in a series of reports, the government emphasised the fractured condition of communities, with the result that Asians and White British individuals were leading 'parallel lives' and self-segregating (Rattansi 2011). While these affirmations have been challenged (Phillips 2006), it remains an issue of debate what mechanisms are associated with the emergence and persistence of ethnic segregation in Bradford. Our study sheds new light on this.

Our analysis shows how the interplay of different micro-behaviours (motivated by homophilic preferences and housing constraints) can lead to varied emergent segregation patterns. We first show that an unrealistic scenario of ethnic over-segregation quickly emerges when agents' residential moves are based solely on their (mild) ethnic preferences, in line with the original Schelling model. However, when socioeconomic conditionings are simultaneously considered, a more realistic segregation scenario emerges. Specifically, a main finding of our study is that when agents' preferences for socioeconomic similarity are slightly stronger than their preferences for ethnic similarity (i.e. when socioeconomic preferences *weight* more), ethnic over-segregation decreases and a segregation scenario closer to the empirical one observed in 2011 emerges. Our work shows that *both* ethnically and socioeconomically motivated residential choices are fundamental for understanding Bradford's overall ethnic segregation patterns. The implications of this outcome and possible mechanisms behind it are discussed in the next pages.

2. Theory and background

2.1. Individuals' preferences and housing constraints in neighbourhood segregation

Different factors explain the spatial allocation of groups and its changes over time (Krysan and Crowder 2017). For the purposes of this paper, we focus on three of them: ethnic preferences, socioeconomic preferences, and socioeconomic housing constraints.

Homophily – the tendency and preference of individuals to interact and share spaces with other that are similar – is known to apply to many categories, including ethnicity and socioeconomic background (Lazarsfeld and Merton 1954; McPherson, Smith-Lovin, and Cook 2001). Homophilic preferences are often developed over the life course, and they are strongly related to lived experiences and social relations built over time (Krysan and Crowder 2017). Homophilic preferences can be key drivers of neighbourhood segregation: to the extent that individuals are raised in areas with certain ethnic or socioeconomic characteristics and interact with similar others (Belot and Ermisch 2009), this will also affect their residential choices and, in consequence, the overall spatial allocation of groups. Ethnic preferences, in particular, can also be associated with wanting to develop social networks and friendships with co-ethnics (Heath and Demireva 2013), reaffirming the own ethnic/religious identity, or increasing the subjective wellbeing (Knies, Nandi, and Platt 2016). At the same time, fear of discrimination or avoiding situations of harassment (Carling 2008; Phillips 2006), can also lead one to prefer a co-ethnic as a neighbour. Similarly, cultural and identitarian factors (Stephens, Markus, and Phillips 2014), as well as factors associated with ease of communication and social exchanges (McPherson, Smith-Lovin, and Cook 2001), can also explain why individuals might prefer neighbourhoods that reflect their own socioeconomic status. These arguments also emerge in the social reproduction literature, where it is argued that people's priority is to maintain their own social class (Goldthorpe 2000; Stephens, Markus, and Phillips 2014). Residing next to individuals with similar socioeconomic characteristics – with whom they can share spaces like schools, social clubs and job centres, and create social ties (Lin 2001) – can be a means towards this aim. [4]

As for the housing constraints considered in this study, they express the socioeconomic structural component of segregation. Having more socioeconomic resources means that individuals can afford wealthier neighbourhoods (which are often whiter too), or that they can more freely choose where to go (Crowder, South, and Chavez 2006). Socioeconomic housing constraints are therefore a main factor that explains why individuals with different socioeconomic resources live in different locations.

All in all, the existence of ethnic and socioeconomic preferences on the one hand and housing constraints on the other – which we consider separately in our modelling –, imply that neighbourhood ethnic segregation might depend on how socioeconomic resources distribute across groups (Krysan and Crowder 2017). More generally, one could hypothesise that if in a certain city all ethnic minorities are poor and all majoritarian white are rich, this might more easily lead to full ethnic segregation; however, if groups are mixed in socioeconomic terms, this may help decrease ethnic segregation, since ethnic preferences will interact with socioeconomic preferences and with housing constraints (Malmberg and Clark 2021). In the UK, ethnic minorities are more often found in neighbourhoods with higher deprivation (Jivraj and Khan 2013; Manley 2021), a fact partly explained by their often-lower socioeconomic resources. However, high-status ethnic minorities also use their resources to improve their neighbourhood (i.e. move to less deprived/whiter areas), in line with spatial assimilation – even though their probabilities of improvement remain lower compared to those observed for white Britons (Coulter and Clark 2019; Zuccotti 2019). These findings point to combined explanations for neighbourhood ethnic segregation in the UK, associated with both ethnic and socioeconomic homophilic preferences and with housing constraints.

2.2. Previous studies building on the Schelling model

The role of socioeconomic resources has been explored by different studies dealing with the Schelling model of segregation. In their study of Swedish cities, for example, Malmberg and Clark (2021) show why income-based sorting can be a factor that counteracts the chance of full segregation as predicted by the Schelling model. They demonstrate that ethnic concentration decreases the housing price of neighbourhoods, and this attracts low-income individuals *both* with and without an ethnic minority background. Conversely, white neighbourhoods become unaffordable for low-income groups, but attractive for individuals who have the means to access them, be these ethnic minorities or not.

The socioeconomic dimension has also been included in several extensions to Schelling's model to reflect more realistic scenarios of segregation. These models include housing costs as an empirical constraint to the relocation moves of people (Bruch and Mare 2009b), as well as additional preferences – next to the ethnic ones – associated with neighbourhoods' quality and amenities, or socioeconomic and status composition, among others (Benard and Willer 2007; Chen et al. 2005). In particular, this stream of literature is interested in formalising how the interaction between unequal income distribution, different preferences and population structure can contribute to spatial sorting between majority and minorities or differences within ethnic groups. Bruch (2014), for example, builds a Schelling-type model where Black and White people select neighbourhoods based on both racial preferences and neighbourhood wealth. Results show that with sufficiently high within-race income inequality, an increase in between-race income inequality is associated with higher probability for lower income Blacks to relocate in an ethnically homogeneous neighbourhood, while the probability decreases for higher status Blacks. Outcomes vary depending on the size of minority.

Fossett (2006, 2011) builds a model with three ethnic groups, where ethnic preferences, preference for neighbourhood socioeconomic status and housing quality interact with one another. He addresses the consequences of such preferences when there are differences in the purchasing power of agents, which are associated with different socioeconomic statuses: the minority agents possessing less resources, but all agents aiming at residing in high-quality neighbourhoods. He shows that native high-status agents can more easily afford high quality neighbourhoods, which hence become also ethnically homogeneous. On the contrary, low income minorities end up in more affordable neighbourhoods that become more ethnically diverse but economically poor (Fossett 2006). Another study with the same model manipulates different scenarios of income inequality between groups, showing patterns of hyper-segregation, i.e. agents with lower income end up in both predominantly ethnic and deprived neighbourhoods (Fossett 2011).

3. Key aspects of our agent-based model

In our agent-based model we follow this stream of literature linking ethnic and socioeconomic characteristics. The aim is to understand whether and how ethnically and socio-economically motivated residential behaviours – potentially conditioned by housing constraints – playout in the emergence of ethnic segregation in Bradford. Our model has the following key aspects. First, we identify socioeconomic status (SES) as one dimension of homophily preference, next to the ethnic dimension. This means that agents in our model consider both ethnic and socioeconomic preferences when evaluating their own residential location and a potential move. Second, we consider a random component that represents other unknown factors that might influence individuals when deciding whether to relocate, and we model the weight of either ethnic or socio-economic preferences over this random component. Third, we consider housing constraints, that is, the affordability and status suitability of relocation moves associated with SES. Finally, we initialise our model with the distribution of the population between ethnic groups, and the distribution of socioeconomic status between different ethnic groups, which is possible thanks to the incorporation of Census geo-referenced data into the ABM.

As regards ethnic and SES preferences, we consider two aspects: agents' preference thresholds and the weights attributed to SES and ethnic preferences. Agents' thresholds refer to the minimal fraction of members of the same group that an individual wants in order to stay in the neighbourhood. The threshold (θ) in our model divides between negative utility (fraction of similar ones below threshold) and positive utility (fraction of similar ones equal or above threshold). Agents search for a new location when they perceive negative utility. Then they compare their location with an alternative one, and choose the one with higher utility. Our model also provides a weight to the role of preferences – be these ethnic or socioeconomic (Bruch and Mare 2006, 2009a; Van de Rijt, Siegel, and Macy 2009). Even with the same threshold for ethnic and socioeconomic similarity in the neighbourhood, agents in our model can give a different importance to ethnicity and socioeconomic characteristics when choosing for a new residence or evaluating their own. In the utility function that we use, weights are expressed in the parameters β_{Eth} and β_{SES}.

Our utility function also considers a random component (ε) to the utility of agents to a particular location, which models any other factor that could influence the utility of a neighbourhood. This includes, for example, any additional neighbourhood amenities (i.e. schools, churches, green areas) that match different household compositions or life-styles, but also preference towards neighbourhoods' openness to diverse ethnic groups (associated with different levels of discrimination in the housing market). The lower the Betas, the higher the weight of the random component will be in the agent's decision, so that the decision either to remain or select another neighbourhood will be taken randomly.

As regards housing constraints, in our model this is referred to as 'tie-houses-to-SES'. With this specification – that we use in our simulations – we acknowledge that individuals are often spatially constrained in terms of the types of locations and houses they can move to, given their socioeconomic resources, that is, they search for and move to houses they can afford. When housing constraints are switched on in our model, individuals are hence constrained to move to free spots that correspond to their own socioeconomic status. Our ABM considers, therefore, two SES dimensions that determine spatial moves, and which are modelled separately (see also Benard and Willer 2007): the above-mentioned SES preferences, on the one hand, and housing constraints, on the other. It might then happen that a high SES agent finds a neighbourhood that matches their SES preferences, but no matching SES houses where to relocate; conversely, he might find a high SES house, but located in a predominantly low SES neighbourhood that does not satisfy their preference, hence preventing the move too.

Finally, ethnic and socioeconomic compositions obtained through empirical data are a key aspect in our model. Specifically, we inform our model with empirical neighbourhood data on ethnicity and socioeconomic resources of individuals, hence narrowing down the possible scenarios that we can formalise to the Bradford case.

4. Bradford: data and key measures

Our analysis uses aggregated 2011 Census data obtained for Bradford at small geographical levels, the Lower Layer Super Output Areas (LSOAs).[5] For each LSOA we collected information on SES by ethnic group. We identified *four ethnic groups* – White British, Asian, Black, and Other ethnic groups (includes other White and mixed groups) – and *three SES groups* – High, Mid and Low. Our analysis is therefore based on Census information making up *12 categories for each LSOA*. Ethnicity is measured with a question on ethnic self-identification; SES is based on the National Statistics Socio-Economic Classification (Erikson and Goldthorpe 1992), and applies to individuals aged 16+ (except for those who never worked, the long-term unemployed and full-time students). Figure 1 shows the distribution of SES categories by ethnic group in Bradford. The SES

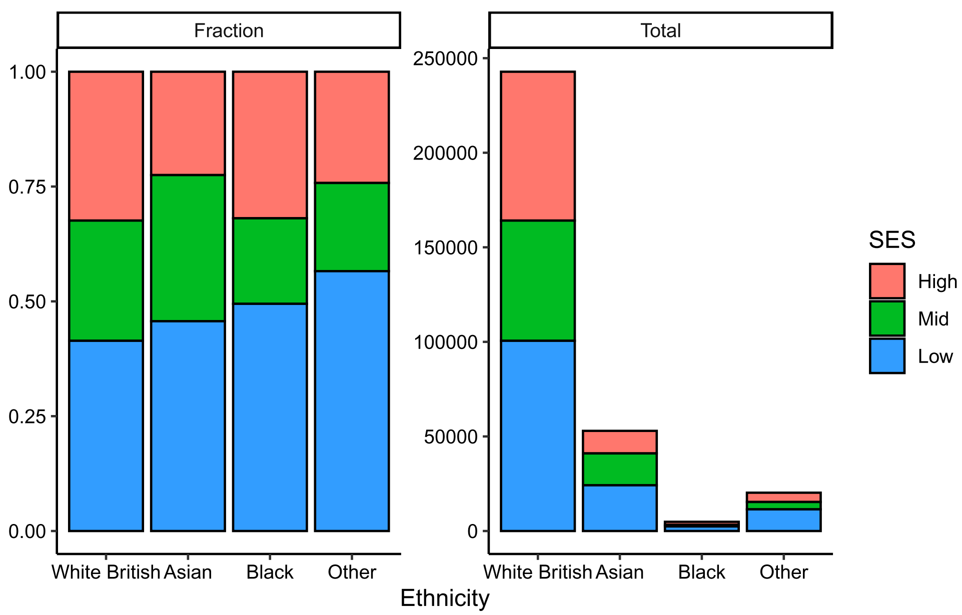

Figure 1. Distribution of SES categories by ethnic group Bradford, 2011. N = 242,835 (White British), 52,954 (Asian), 4,880 (Black), 20,252 (Other).

distribution is quite similar across groups, even though the proportion of individuals without a valid SES is higher among ethnic minorities. Further details about the data, variables, and their limitations, are discussed in the Online Annex.

The key outcome variable of our ABM is the distribution of ethnic minorities in LSOAs, which we measure with the fractions of ethnic groups in LSOAs (see Figure 2). Further on, we focus on three indices: *Dissimilarity Index, Average Local Simpson Index* and *Moran Index of spatial autocorrelation*.

The Dissimilarity Index is a measure of the evenness with which an ethnic group is distributed across geographic areas (LSOAs) that make up a larger area (Bradford LA). The index indicates the percentage of members of that group that should relocate to let the distributions at the LSOA levels match the distribution at the town level. The Dissimilarity Index is highest for Asians (0.66, see Figure 2).

The Simpson Index, which can be calculated for each LSOA (local) and for the whole town, is a measure of ethnic concentration. It expresses the probability that two randomly selected individuals from the LSOA/town have the same ethnicity. To calculate this index we only consider White British, Asians, and Blacks, leaving outside 'other ethnic groups'. We do so upon the consideration that individuals from this group are less likely to recognise each other as similar in terms of ethnic preferences. The town-wide Simpson Index is $S_{\text{Town}} = 0.6$.[6] This number serves as a reference to compare with the Average Local Simpson Index that we use in our study, which is the population weighted average of the Local Simpson Index values in all LSOAs. When it is much larger

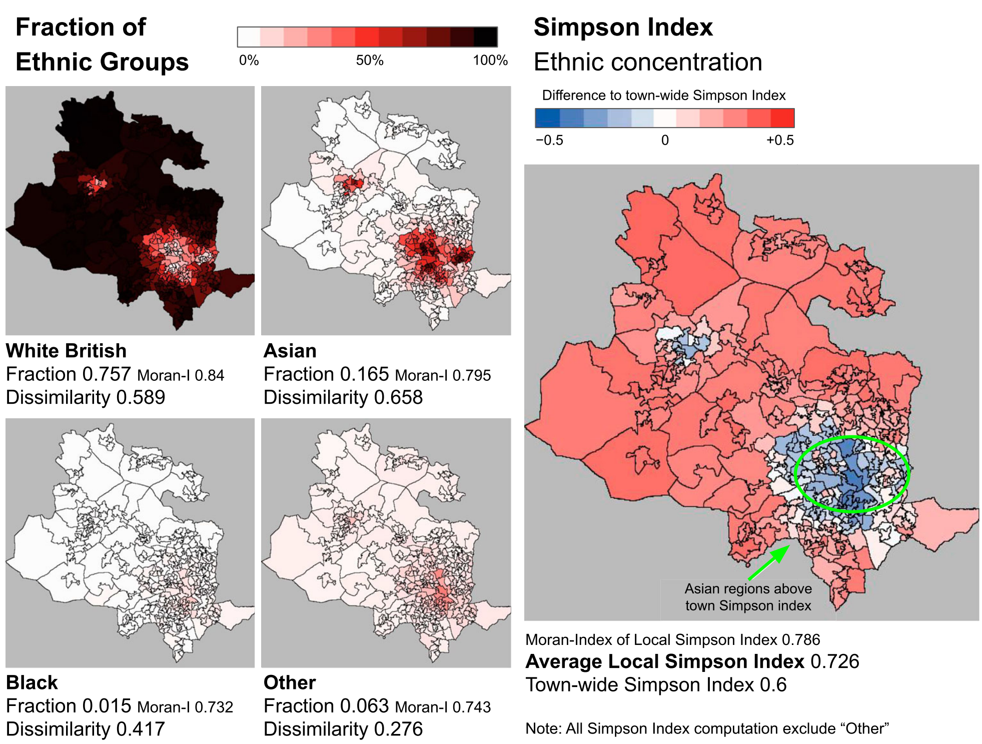

Figure 2. Distribution of ethnic groups and segregation indices. Bradford, 2011.

than the town-wide Simpson Index, this indicates strong local concentration (see also red areas in Figure 2). In Bradford, the Average Local Simpson Index it is $S = 0.726$. This means that the probability that a randomly selected pair of individuals from the same LSOA is from one ethnic group is 72.6%, while this would only be 60% when the pair is sampled randomly from the whole town.

The Moran Index (Moran-I), finally, computes the spatial autocorrelation, i.e. the tendency for neighbouring areas to report similar values of a certain characteristic such as ethnic concentration, across LSOAs. It ranges from −1 to 1. The value of 0.78 for the Local Simpson Index in Bradford denotes high spatial autocorrelation based on ethnicity. All indices' formulas are in the Online Annex. The numbers in Figure 2 build the basis for our data-driven model building and calibration.

5. Agent-based model

5.1. Model setup

Our ABM is built in NetLogo 6.1.1 (Wilensky 1999), which is a modelling environment made for agent-based modelling and simulation. In the model, each *agent* represents an individual specified by *ethnicity* ('WHITEB', 'ASIAN', 'BLACK', or 'OTHER'), *socioeconomic status* ('LOW', 'MID', or 'HIGH'), and an individual *threshold* value that quantifies the minimal fraction of similar neighbours (in term of ethnic or socioeconomic status) the agent needs to be satisfied with their current location.[7] Each agent is located in one of the 306 LSOAs in Bradford, which are loaded into the model upon initialisation using NetLogo's GIS extension. The *neighbourhood* of an agent is constituted by all other agents in the same LSOA and, with a lower weight, those agents in geographically neighbouring LSOAs.

At each unit time step, agents make relocation choices. We model a unit time step such that, on average, every agent makes one relocation choice per time step. An agent's *decision to relocate* is modelled as a two-step process: the decision to search and the decision to move. First, the agent assesses the utility of their current residence. When utility is positive, the agent stays, and the second step is skipped. When utility is negative, the agent compares their current residence to a random alternative and chooses the one with larger utility. With the two-step process, we unite two traditions of relocation models. In the first tradition (Schelling's original model), agents only decide to leave to a new place once their neighbourhood doesn't satisfy their utility (step one), without checking if utility would improve. In the second tradition, subscribing to discrete choice models (Bruch and Mare 2009a; Xie and Zhou 2012), agents always compare their current residence with other options (step two), selecting the one with the highest utility. In our model, they only do this if they already have negative utility at their current location.[8]

Formally, an agent with ethnicity X, socioeconomic status Y, and threshold θ computes *utility* for a residence in LSOA i as

$$U_{(X,Y,\theta)}(i) = \beta_{\text{Eth}}(P_i^X - \theta) + \beta_{\text{SES}}(P_i^Y - \theta) + \varepsilon,$$

where P_i^X is the fraction of the population with the same ethnicity, P_i^Y the fraction of the population with the same socioeconomic status and ε is the unobservable utility of the agent. The first two terms on the right-hand side are the observable utility. The parameters β_{Eth} and β_{SES} represent the weights for similarity in ethnicity and similarity in socioeconomic status in the relocation choice in comparison to the random component ε (Manski 1977).

In step one of the relocation decision, the agent decides to search when $U_{X,Y,\theta}(i) < 0$. In step two, the agent selects an LSOA j to potentially move to, based on a random probability proportional to the number of free residences over all districts.[9] With the option *tie-houses-to-SES* switched on, the model keeps track of three different types of houses, one for each SES. That means, e.g. an agent of SES HIGH will only search for free houses for individuals of SES HIGH. The agent relocates to district j when $U_{X,Y,\theta}(j) > U_{X,Y,\theta}(i)$, leaving a spot then available in district i. Utility increases linearly with P_i^X as well as with P_i^Y. Thus, low similarity in ethnicity can be compensated by high socioeconomic similarity and vice versa. Unobservable utility ε represents all unknown factors influencing the agent. Whenever utility is assessed, a random number for ε is drawn from a standard Gumbel distribution.[10] The lower β_{Eth} and β_{SES} are, the stronger is the impact of the random term. With $\beta_{\text{Eth}} = 0$, ethnic similarity doesn't influence the relocation decision, for $\beta_{\text{SES}} = 0$, socioeconomic composition doesn't matter. A random term in the utility function is a standard assumption in discrete choice models to represent how people, though maximising utility, might not always select the best option based on observable utility (Hess, Daly, and Batley 2018; Train 2009); it is also well-established in empirical studies of residential mobility (Boschman and Van Ham 2015; Frankhauser and Ansel 2016). In our case, it is reasonable to treat the ethnicity OTHER as done for the Simpson index: assuming they will perceive themselves as much less similar. Therefore, we set $\beta_{\text{Eth}} = 0$ when $X = \text{OTHER}$.[11]

The random term of unobservable utility and the random selection of alternatives make ours a stochastic model. Nevertheless, our model reaches segregation patterns looking like stochastic equilibria. That means, fractions of ethnicities stay constant, although every time step agents are still moving. A deeper mathematical analysis of equilibria and their stability is outside the scope of this paper. Note also that we do not model changes in the SES of individuals nor changes in the SES of houses. Such processes are of course relevant in the real world related to rising unemployment, upward mobility, and degradation or gentrification of neighbourhoods. Given the already complex nature of our model, we leave these additional factors for future research. We provide additional technical descriptions of the model's implementation in the Online Annex.

5.2. Analysis

We performed a parameter exploration to find a possible explanation of how ethnic residential segregation levels similar to those empirically observed in Bradford could emerge even from a *counterfactual maximally non-segregated town*, that is, from a situation in which each LSOA has the same ethnic composition (Edmonds et al. 2019; Epstein 2006). We searched for a combination of the parameters μ_θ (average threshold), σ_θ (heterogeneity of thresholds), β_{Eth} (weight for ethnic similarity), β_{SES} (weight for socioeconomic similarity), and *tie-houses-to-SES*. To that end, we scaled down Bradford's population by 10 to speed up computations. So, every simulation ran with about 32,180 agents, on average 105 per LSOA.[12] The exploration started with reasonable parameters settings, based on educated guesses or plausible arguments. The resulting outcome was assessed qualitatively looking at the spatial patterns and some macroscopic segregation indicators. Next, configurations were chosen narrowing to a systematic scanning in a limited parameter range.[13] Our exploration ended with the specification of a main parameter constellation that best approximates to Bradford's spatial patterns in 2011. In the following, we first present this constellation and show how it matches the empirical segregation pattern in Bradford. Afterwards, we decompose this parameter constellation to explain the emergent mechanisms: First, we analyze ethnic preferences alone and threshold heterogeneity; next, their interplays with socioeconomic preferences and socioeconomic housing constraints. While all four ethnic groups are considered in the coming analyses, we focus our discussion on the largest group, the Asians.

5.2.1. Main parameter constellation

The following parameters reproduce several characteristics of Bradford's empirical situation of ethnic segregation in 2011: $\mu_\theta = 0.3$, $\sigma_\theta = 0.1$, $\beta_{\text{Eth}} = 8$, $\beta_{\text{SES}} = 12$, *tie-houses-to-SES* switched on.[14] The standard deviation of $\sigma_\theta = 0.1$ implies that less than 2% of all agents are already satisfied with less than 10% similar, while also less than 2% would demand more than 50% similar to stop searching for other options. The outcome of the simulation after 2,540 timesteps is shown in Figure 3. Simulation outputs almost stabilised at this stage, so the model seems to be close to a stochastic equilibrium. A deeper theoretical analysis specifically about the equilibria of the model is beyond the scope of this study. A detailed description of Figure 3 and steps to reproduce the simulation are shown in the Online Annex. Furthermore, our NetLogo model is freely available, along with the data, in Lorenz (2022) (see also data availability statement at the end of the article).

Figure 3 shows two smaller clusters of LSOAs in the north and two bigger clusters in the south-east are visible with more than 60% Asians (central map), surrounded by LSOAs with around 30–50% of Asians. Some regions exist with 4–8% of Asians. Most of the other districts have close to zero Asians. This is similar to Bradford's empirical configuration in 2011 (see Figure 2). Figure A1 (in the Online Annex) shows the time

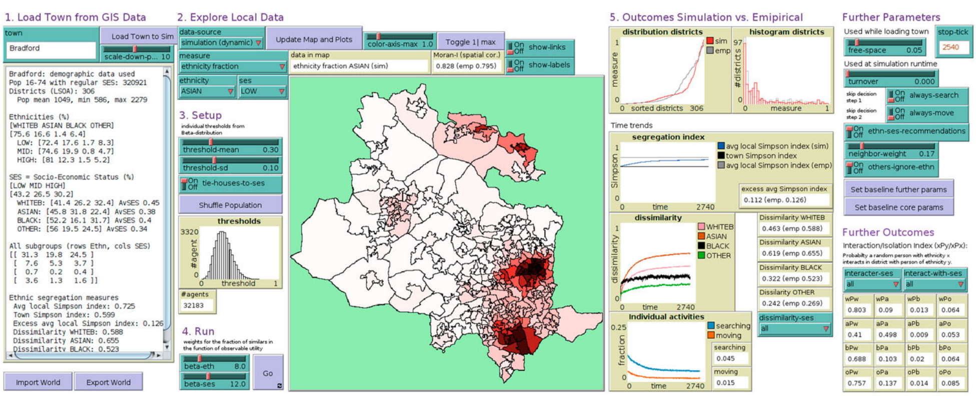

Figure 3. NetLogo Interface, and simulation outcome at time step 2,540 with the main parameter constellation. The map shows the fraction of Asians.

evolution of the fraction of Asians in a sequence of maps to provide more detail on ethnic clustering. It also provides the outcomes of three other simulations run with the same parameters to demonstrate how they would not differ in terms of segregation levels, despite random fluctuations in the geographic configuration. The exact geographical configuration of ethnic clusters evolves to a large extent based on reinforcement of initial random fluctuations.

The outcomes of the simulation shown in Figure 3 show that levels of spatial segregation of Asians close to empirical data emerge from a spatially equalised population with intermediate preferences for ethnic similarity ($\beta_{\mathrm{Eth}} = 8$) but even stronger preferences for similarity in socioeconomic status ($\beta_{\mathrm{SES}} = 12$). Segregation happens even though agents are on average already satisfied with a mild preference of 30% similar neighbours ($\mu_\theta = 0.3$), so that on average an agent would be fine with living in an LSOA as a minority concerning ethnicity and socioeconomic status – Asians and White British alike. The Moran Index of spatial autocorrelation for the fraction of Asians is 0.82 in the simulation, very similar to the empirical value of 0.799 (note that all measurements refer to a population with a valid SES). The figure also shows that the simulated distribution of Asians is quite similar to the empirical distribution (see Section 5. Outcomes Simulation vs. Empirical), with the difference that the simulation shows slightly more districts with less than 10% Asians but slightly less with 10–60% Asians. Looking at other measures, the average local Simpson Index starts with 0.599, and then it increases over time up to the level 0.711 close to empirical observations in Bradford in 2011. As in Bradford's empirical data, the dissimilarity of Asians grows highest, with White British second. The small fraction of Blacks has the third largest dissimilarity and other ethnic groups the lowest, which coincides with empirical observations. Interestingly, the dissimilarity of ethnic groups in the category 'Other' also increases over time, although in our simulation these agents do not consider ethnic similarity in their decision to relocate, differently from the other three groups. The fraction of agents relocating declines over time because people tend to be satisfied. After the 2,540 time-steps still 4.5% of agents decide to search an alternative and 1.5% of the people move.

Why do these segregation patterns emerge out of equally distributed ethnic groups in LSOAs, that is, out of an initial ethnically non-segregated Bradford? A reinforcing mechanism is at play, following four basic steps:

(1) Random fluctuations happen through random draws of unobservable utility, which perturbs the perfect equality of LSOAs' demographic compositions.
(2) An agent who searched for a new location is more likely to move to a LSOA with more agents of their kind (in ethnicity or socioeconomic status), even if they would remain unsatisfied afterwards. Agents who have positive observable utility tend to stay. Staying is very likely for White British individuals but unlikely for Asians (and Blacks) in the initial condition (due to White British individuals' higher numerosity). Thus, in the beginning, Asians will move more than White British individuals and more likely to districts with slightly more Asians. This mechanism can drive an increase in the fraction of Asians in LSOAs with few Asians.
(3) Once the fraction of Asians in a district exceeds the average threshold of 0.3, Asians in that district are more likely to be satisfied and to not search anymore for

alternatives. Such a district becomes persistently more attractive for other unsatisfied Asians, in addition to Asians there already satisfied. White British individuals also have positive utility there but, due to their higher numerosity, there are many more options equally satisfying for them than for Asians. This mechanism spurs the increase of the fraction of Asians in LSOAs with already a sizable fraction of Asians.

(4) Finally, if the fraction of Asians approaches 70% (one minus the average threshold) most White British are likely to receive negative utility from the LSOA's ethnic composition so to start searching better alternatives. This drives the evolution towards an all-Asian district.

If these mechanisms would have continued to work alone, Bradford would have ended up with all Asians and White British concentrating in fully homogeneous districts (see more details in section 5.2.2). However, the mechanisms of socio-economic similarity and housing constraints have mitigated this reinforcement. Specifically, some weight on socio-economic preferences can mitigate the drive towards full ethnic segregation because individuals now also draw utility from living with neighbours of similar socio-economic status, even when these have another ethnicity. The role of housing constraints (*tie-houses-to-SES*) has a smaller impact on ethnic segregation: the emerging patterns of ethnic segregation ultimately rely, thus, on preferences of agents rather than stemming from their affordances against housing constraints. However, without housing constraints we obtain a much higher socioeconomic segregation than observed in reality. Hence, while not affecting ethnic segregation so much, housing constraints do prevent this dynamic towards districts with unrealistically high fractions of low and high SES individuals. The inclusion of this factor provides, therefore, with a more realistic scenario of Bradford's ethnic and socioeconomic structure. We point this out more explicitly in the following.

5.2.2. Other parameter constellations

In the following, we show more simulation output starting with ethnic preferences alone and a homogeneous threshold. Then we introduce, step by step, heterogeneous thresholds, preferences for socioeconomic status, and *tie-houses-to-SES*, to arrive at the final parameter constellation presented above.

Figure 4 shows simulation output with different weights for ethnic preferences ($\beta_{\text{Eth}} = 4, 8, 12$) and no socioeconomic preferences ($\beta_{\text{SES}} = 0$). Further on, simulations ran with a homogeneous threshold $\mu = 0.3$ ($\sigma_\theta = 0$) or heterogeneous thresholds ($\sigma_\theta = 0.1$) as in the final constellation. All simulations ran for 1,260 time-steps. Results show two qualitatively different outcomes. For high ethnic similarity weights, Asians gather and satisfice in several LSOAs with 20% to 30% Asians with no larger Asian fraction in other LSOAs. For low weights and thus more random fluctuations, almost all Asians finally end up in 100% Asian districts. This result may appear counterintuitive because one might think that a higher weight for ethnic similarity would indeed trigger more ethnic segregation. The reason is that without random fluctuations, the mechanism (4) could not kick in and no LSOA would reach the threshold at which White British individuals massively leave. Random fluctuations can create a seed for all-Asian districts, making also

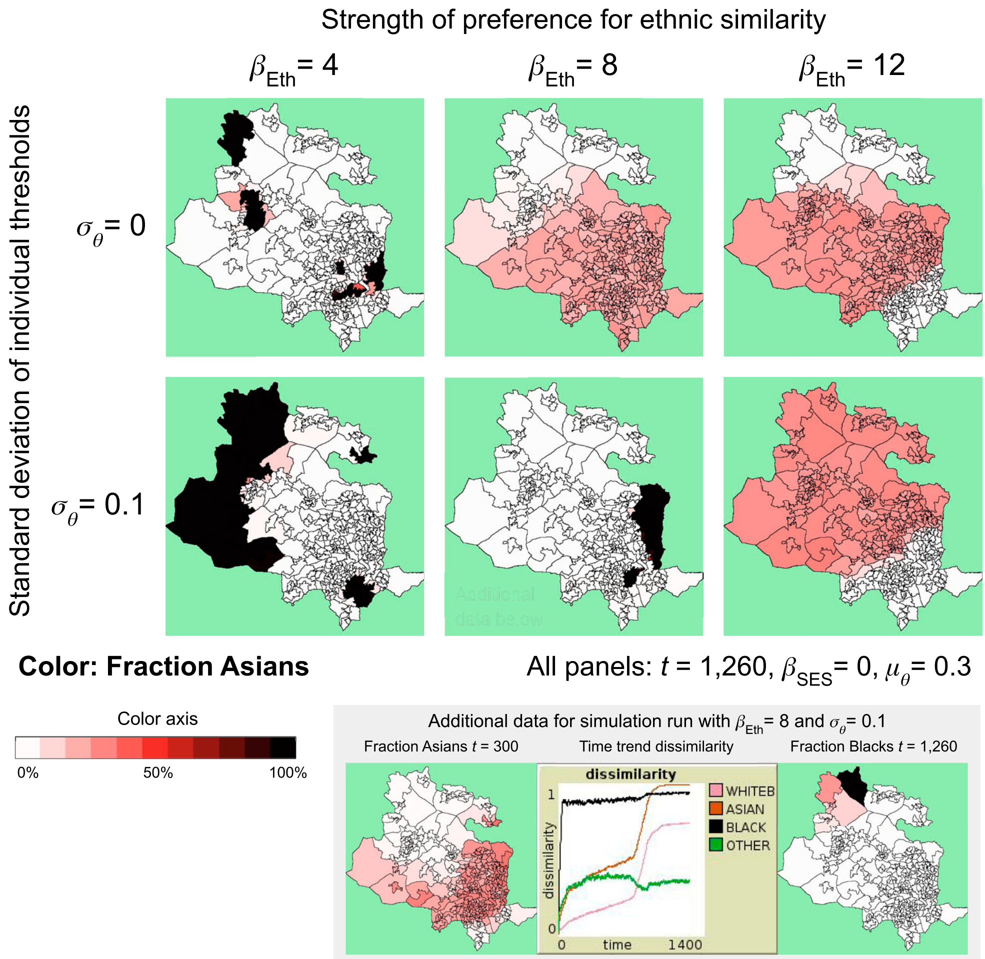

Figure 4. Exploration of the preferences for ethnic similarity and threshold heterogeneity focusing on the fraction of Asians including further details for one simulation at the bottom.

neighbouring districts attractive for Asians. The heterogeneity of thresholds seems to contribute to this, as visible in Figure 4. For the intermediate weight of $\beta_{\text{Eth}} = 8$, all-Asian districts only emerge under heterogeneous thresholds. The case with heterogeneous thresholds is also interesting as shown in the grey extra box in Figure 4: after 300 timesteps the situation looks as for homogeneous thresholds. Only after about 800 timesteps the dissimilarity index of Asians quickly increases and the whole town shifts to full segregation. Such sudden drastic changes are a common possibility in dynamic models. Also, the small Black population could form a cluster with one all-Black district in this simulation run.

In Figure 5 we show the effect of preferences and housing restrictions concerning socioeconomic status. While Figure 4 showed that an intermediate level of $\beta_{\text{Eth}} = 8$ together with threshold heterogeneity $\sigma_\theta = 0.1$ enabled the emergence of all-Asian districts, this exaggerated the empirical situation of ethnic segregation in Bradford, as no ethnically diverse districts remained. Figure 5 shows the effects of increasing weight for socioeconomic similarity β_{SES}. Further on, it introduces that houses are tied to the socioeconomic status of residents. Both the condition $\beta_{\text{Eth}} = 8$, $\beta_{\text{SES}} = 12$ with *tie-houses-to-SES* and the condition $\beta_{\text{Eth}} = 8$, $\beta_{\text{SES}} = 8$, without *tying-houses-to-SES*, deliver both results close to empirical observations. However, in the condition $\beta_{\text{Eth}} = 8$, $\beta_{\text{SES}} = 8$ socioeconomic segregation would be much higher than in reality

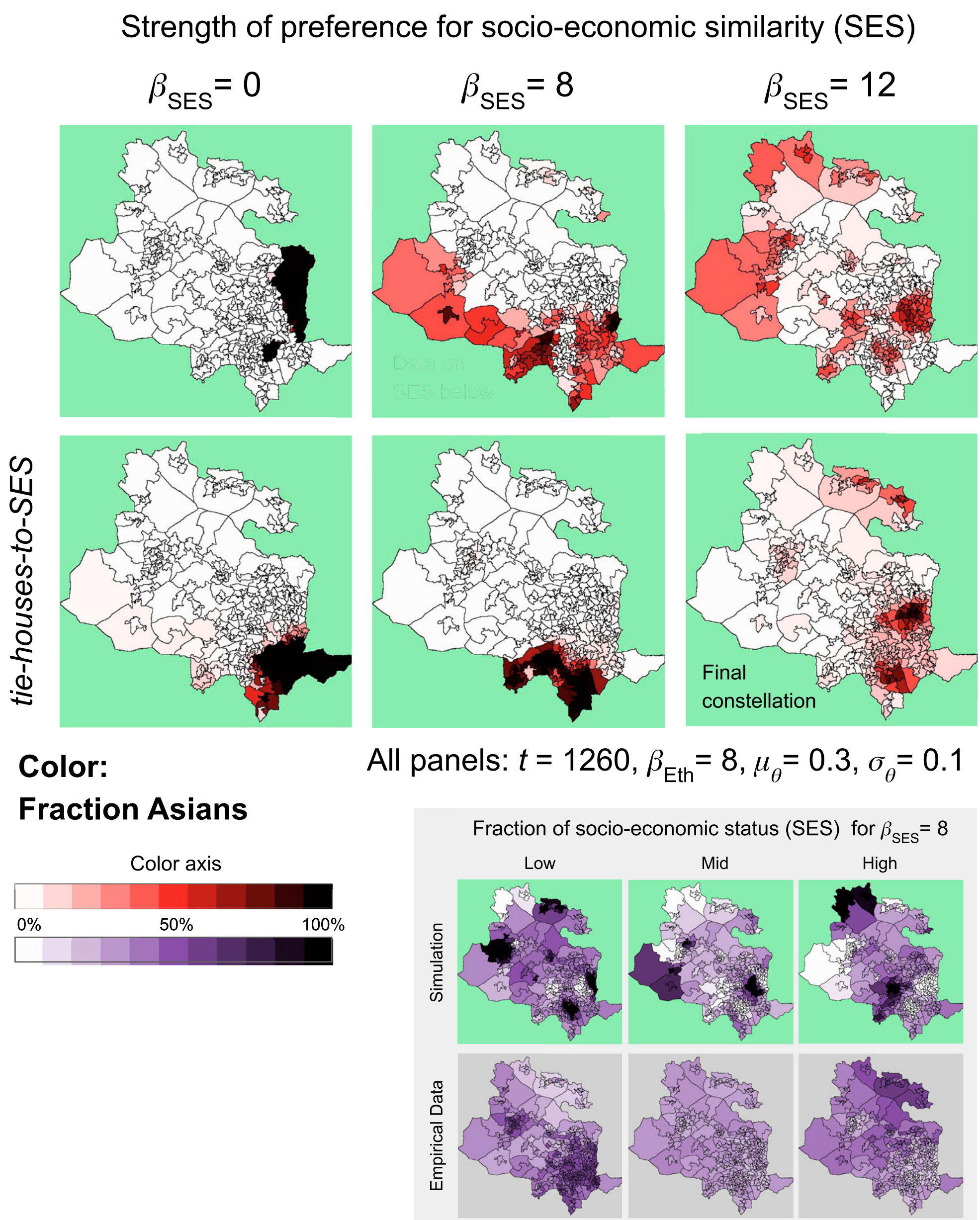

Figure 5. Exploration of the preferences for socioeconomic similarity and tying houses to socioeconomic status focusing on the fraction of Asians including the baseline parameter constellation. Further details about SES segregation for another simulation at the bottom.

as the grey box at the bottom of Figure 5 shows. To avoid this over-segregation by SES that deviates from empirical observations, we consider the condition of *tie-houses-to-SES*, which preserves much of Bradford's sociodemographic structure. Note, nevertheless, that the role played by housing constraints on obtaining a realistic ethnic segregation scenario is minimal as compared to the role played by agents' SES preferences. The simulation stabilises without ethnic over-segregation only when the weight for socioeconomic similarity *outweighs* ethnic similarity, with results similar to the ethnic empirical segregation in Bradford in 2011 ($\beta_{\mathrm{Eth}} = 8$, $\beta_{\mathrm{SES}} = 12$; see panel 'Final constellation' in Figure 5). The mitigating effect that SES preferences have on ethnic segregation happens because some Asians accept less ethnically homogeneous neighbourhoods to satisfy their SES preferences.

6. Summary and discussion

Neighbourhood ethnic segregation remains an issue in many societies and continues to feed debates on ethnic inequalities and on the routes towards social cohesion. Despite extensive literature on the changes and effects of segregation, a main challenge is to address the underlying processes that explain segregation as an aggregate emergent phenomenon derived from individuals' behaviours and their constraints (Bruch and Mare 2009b). Inspired by the field of analytical sociology and using agent-based modelling – a method that allows formalising the link between individual decisions and emergent phenomena – our paper has helped filling in this gap. Specifically, we extended Schelling's agent-based model, and studied how ethnic and socioeconomic homophilic preferences and housing constraints interact to create varied emergent segregation patterns. We modelled the relocation decision of agents following a discrete choice random utility approach, simulating different weights for preferences for ethnic and socioeconomic similarity in neighbourhood composition over random relocations. In addition, we included socioeconomic housing constraints to the actual relocation move. We used Bradford – a high ethnically segregated LA in the UK – as a case study and initialised our model with empirical geo-referenced data about ethnicity and SES from the 2011 Census.

Results show, as in the original Schelling model, that strong ethnic segregation would emerge as an effect of relocation moves of individuals, also in case of mild preferences for ethnic similarity and starting from an artificially equalised spatial distribution. However, our additional consideration of socioeconomic factors in the model has proven to counterbalance this extreme result. We show that segregation patterns close to empirical observations, without ethnic over-segregation, are reached when preferences for socioeconomic similarity are slightly above the preferences for ethnic similarity. In particular, this dynamic seems to take place because Asians give up on ethnic homophily preferences in order to satisfy socioeconomic homophilic preferences. This is in line with some aspects of spatial assimilation theory and more generally with the well-known role that SES plays in ethnic segregation (Malmberg and Clark 2021; Massey and Denton 1985). While socioeconomic housing constraints do not seem to play a major role in ethnic segregation in our model, they do prevent over-segregation by SES, therefore improving the reproduction of Bradford's spatial structure overall.

Our work has important implications that can help enrich both policy (see e.g. HM Government 2018; HM Government 2021) and academic debates on segregation dynamics. This paper demonstrates, *first*, that spatial fractioning of ethnic communities might not necessarily reflect a prejudice towards other ethnic groups or the intention to self-segregate, as the 'parallel lives' thesis would state. Rather, high ethnic segregation can be the unintended consequence of simple relocation moves of individuals who want to satisfy their preferences to live close to just a few similar ones. In fact, ethnic preferences alone do not lead to a realistic picture of ethnic segregation in Bradford, but to over-segregation. *Second*, our results show that the process that leads to full segregation due to ethnic preferences can be altered in favour of less ethnic segregation when people care more about socioeconomic similarity than about ethnic similarity. This implies that while tackling inter-group prejudice and promoting ethnic and migrant integration remain important for increasing ethnic mixing in neighbourhoods and improving intercultural contact – as also evidenced by Kelling and Monroe (2022) –, investigating the role of socioeconomic factors in relocation decisions can also be helpful. This includes further explorations not only of how housing affordability may affect ethnic segregation, but also and most importantly, of how individuals' inclination to live close to members of the same socioeconomic group may alter both ethnic and socioeconomic spatial landscapes. *Third*, our work shows evidence of the potential of combining computational approaches with geo-referenced data to study the relationship between social and spatial processes. The increasing availability (and level of detail) of this type of data, coupled with the constant evolution of computational methods, will likely allow for this kind of research to further develop in the next years. The work of Pettrachin et al. (2022), who exploit fine-grain spatial data with spatial regression models, is also clear example of this. *Finally*, by providing a freely available and reproducible model, our work may be useful to researchers and policy makers interested in simulating policy interventions (e.g. a labour policy that impacts the distribution of SES across ethnic groups) and testing their spatial consequences.

We acknowledge some limits of our work that can contribute to develop future lines of research. Even though we modelled a heterogeneous distribution of thresholds of agents, we did not differentiate their weights for ethnicity or socio-economic preferences (apart for ethnic preferences of Others). Although not a realistic assumption, this was done to not overly increase the complexity of the model so to better understand its dynamics. In the future, we could vary threshold or weights of individuals according to their ethnicity or socio-economic status, or as a combination of both to cover more detailed or realistic scenarios. Second, our model does not consider other factors affecting residential moves and/or spatial segregation more generally, such as ethnic discrimination, household composition, friendships and social networks, fertility, or migration patterns from/to Bradford. Further research would certainly benefit from including such dimensions in the models to observe how the mechanisms we identify would change or not. Finally, our results stem from the exploratory calibration of the model with Bradford data. In the future we could compare with other cities differing by ethnic or SES distribution in the population. This could shed further light on the role of population composition in causing our results and increase the generalizability of results to the UK context and beyond.

Notes

1. We are aware that there are other factors affecting residential moves and/or spatial segregation patterns overall, such as housing discrimination (Roscigno, Karafin, and Tester 2009), fertility, migration (Finney and Simpson 2009) and family relations (Peach 2005). We do not include these in our analysis to keep it more focused, and because of analytical constraints.
2. As pointed out by Hegselmann (2017), the model likely goes back to Sakoda's work.
3. https://ubd.bradford.gov.uk/about-us/poverty-in-bradford-district/ (last access December 9th 2021).
4. There are alternative factors that may affect neighbourhood choice, such as low-status aversion or high-status attraction (for details see Galster and Turner 2019). They may be the object of future study.
5. Specifically, we used data from Table ID LC6206EW, retrieved from https://www.nomisweb.co.uk/ on March 23, 2020. 'This dataset provides 2011 Census estimates that classify usual residents aged 16 and over in England and Wales by NS-SeC, by ethnic group and by age. The estimates are as at census day, 27 March 2011' (https://www.nomisweb.co.uk/census/2011/lc6206ew).
6. The focus on the population with a valid SES has notable consequences for the Bradford's town-wide Simpson Index which would be only $S = 0.48$ otherwise, mainly because of the higher share of Asians in the total population.
7. The threshold is an individual static variable of each agent. We assume that thresholds are heterogeneous among agents. As thresholds should be between 0 and 1, a natural assumption is, that they come from a Beta distribution. The agents' thresholds are randomly drawn upon initialization.
8. In the model, we provide a switch to make agents always move and a switch to make them always search.
9. The probability is additionally weighted by the fractions of those with the same ethnicity and those with the same socioeconomic status, similar to the computation of utility. This specification models the feature that an agent might receive recommendations coming from ethnic of socio-economic peers. The feature can be switched off with the parameter *ethn-ses-recommendations*.
10. The Gumbel distribution is also known as generalized extreme value distribution type-I. It has a mean of 0.577 and a standard deviation of 1.283. In decision step 2, two random numbers are compared, one for each alternative. The difference of two Gumbel random variables has a logistic distribution with mean zero and standard deviation 3.29.
11. The model includes a switch to treat OTHERS like a normal ethnic group.
12. We tested extensively that simulation runs are like simulations with the full population.
13. We refrained from implementing an automatic optimization for this study for two reasons: First, computation time is long, and (as we see later) stabilization of parameters is difficult to assess automatically. Second, a general performance measures comparing data and simulation is difficult to define properly. That could be an option in future studies with a more mature understanding of model dynamics.
14. We set free-space = 0.05 and neighbour-weight = 0.17 after some exploration. A further analysis of these parameters' impact is beyond the scope of this study.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available in the following repository: janlorenz/Schelling_on_GIS: (v1.0). Zenodo at https://doi.org/10.5281/zenodo.6604564 (Lorenz 2022). These data were derived from the following resources available in the public domain: Table ID LC6206EW from https://www.nomisweb.co.uk/ and LSOA shapefiles from http://geoportal.statistics.gov.uk. The data is presented in shapefile format. The repository also contains the code for the agent-based model built in NetLogo 6.1.1. The Online Annex provides instructions on how to reproduce the agent-based model.

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