City affordability and residential location choice: A demonstration using agent based model

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**ABSTRACT**

Who lives where and why? – is a prominent issue studied in the field of urban economics. With urbanization on the rise, housing and transportation policies must strive to strike a balance between accessibility and affordability. The study builds an economic rational agent-based model, for a hypothetical monocentric city, to simulate the urban pattern that emerges from households’ residential location choice as they aim to minimize their expenditure on rent and commute under different scenarios. The model highlights the significance of housing and transportation costs as a spatial policy tool in shaping urban growth. By manipulating these costs, cities can promote compactness, increase affordability, and result in a more homogeneous density and income distribution pattern. The study also finds that mode of travel plays a crucial role in determining residential choice, with private transportation users tending to reside in the city’s inner areas and public transportation users opting for outer areas. However, when public transportation is heavily subsidized, this pattern is reversed. We also find that an increase in income inequality and plot size variability can lead to income-based segregation in the city. Our study findings, validated through a review of the relevant empirical literature, provide valuable policy directions into the underlying mechanisms that shape the urban growth pattern.

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1. Introduction

The choice of a household’s residential location is influenced by a multitude of factors, including the residential density (Lindert & Westen, 1991), access to public amenities and employment opportunities (Baraklianos et al., 2020), the neighbourhood’s physical and natural characteristics (Gbakeji & Magnus, 2007), the cost of housing and plot size (Yi & Lee, 2014), and proximity to similar communities (Guidon et al., 2019). Despite a household’s desire to optimize all of these factors, budget constraints often limit their options (Kutty, 2005). According to the 2020 Consumer Expenditure Survey, housing and transportation expenses account for the largest portions of a household’s budget in the United States, representing 15% and 12% of their income, respectively (U.S. Bureau of Labor Statistics, 2021). While these two expenditures are significant, they are also interrelated, with higher accessibility to employment opportunities often corresponding to higher housing costs and lower commuting expenses (Haas, Makarewicz, Benedict, Sanchez, & Dawkins, 2006). As households are bound by a fixed budget, they must make trade-offs between housing and transportation costs in order to maximize their overall utility (Weisbrod et al., 1980).

As each household aims to maximize its utility, the interplay between demand and availability of preferred residential locations leads to the formation of complex urban patterns (Carrión-Flores & Irwin, 2004). These patterns are the result of the interplay between individual household location choices and housing regulations policies. The evolved urban pattern can be characterized by several parameters such as residential density, land-use mix, plot size, residential segregation, and income distribution. Previous studies have found that these parameters vary with distance from the city centre and between affluent and disadvantaged neighbourhoods (Gelormino et al., 2015; Zhao et al., 2018). Moreover, the degree of variation varies across cities of different sizes, populations, and land-use policies. While the impact of housing and travel affordability on household location choices and the resulting urban morphology has been analyzed through various economic models, only a few studies have simulated these relationships (Yen et al., 2019).

The study builds an economic rational agent based model to simulate the urban pattern that emerges from households’ residential location choices as they make decisions to minimize their expenditure on rent and commute under different scenarios. The scenarios are created by varying housing and transportation cost, income inequality, mode of

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0197-3975/© 2023 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
travel, and occupied area. The study sets three objectives: (a) to examine the trade-off between rent and commuting expenditure as reported in traditional location choice models, (b) to understand how to make residential density more homogeneous across the city to avoid overcrowding and sprawl, and (c) to investigate the impact of unequal income and land ownership distribution on residential segregation. It is important to note that the model only considers rent and commuting expenses in determining household location choices. While other factors such as proximity to friends and family, neighbourhood vibrancy, and access to green areas may also impact location choice, this study assumes households to be rational economic agents who aim to maximize their utility by minimizing expenditure. Adding more factors to the model would complicate the model design and operation and detract from the study’s aim of simulating the possible urban pattern that may emerge as cities become more or less expensive for households.

The study’s major contribution lies in simulating some of the complex phenomena of urban development concerning city size and residential segregation. With an understanding of how the residential location choice of different income households varies with city affordability, appropriate policies can be made to solve these issues and promote more equitable urban development. By incorporating various factors such as housing and transportation cost, income distribution and land ownership in a city, the simulation results provide valuable insights into the underlying mechanisms that shape the urban growth pattern. This can inform policymakers and urban planners to make data-driven decisions aimed at improving the livability and sustainability of cities.

The structure of the paper is as follows: Section 2 provides a brief literature review on household expenditure and location choice. In Section 3, we outline the design and calibration of the Agent-Based Model (ABM). In Section 4, we present the results from the ABM simulation. Section 5 validates and discusses the findings of the model, and finally, Section 6 concludes the paper.

2. Literature review

The Sustainable Development Goal (SDG) 11 aims to make cities more resilient and sustainable by providing better access to public transportation and affordable housing for all. However, current practices in urban policy and planning tend to address these issues separately instead of in an integrated manner (Nakamura & Avner, 2021; Waddell et al., 2003). Research shows that improving access to public amenities in a neighbourhood can lead to higher rent prices, making housing unaffordable for low-income individuals (Brueckner et al., 1999; Corrigan et al., 2019; Hamilton & Roell, 1982; So et al., 2001). The trade-off between rent price and commuting cost has been explored in examining household residential location choices and average commuting distance. One of the seminal theories in urban economics that conceptualise and model household location choice is the Alonso-Muth-Mills Model (AMM), formulated by Wheaton (1974). According to the AMM, in a monocentric city, density and rent price decreases with distance from the city centre while household plot area and commuting cost increases. The combined expenses on housing and transportation reach an equilibrium where a decrease in housing price is offset by an increase in transportation cost and vice versa.

Many other traditional urban economic models also assume this perfect tradeoff between housing and transport expenditure (Mattingly & Morrissey, 2014). However, the empirical evidence from different cities clearly shows that living cost in cities is not the same for all households. It is un-equally affordable for households across space and socio-economic groups (Dewita et al., 2020; Makarewicz et al., 2020). The reason behind this inequality in living costs is largely twofold: income inequality and location efficiency. High income inequality results in poor income households spending a higher percentage of their income on housing and transportation, even at locations where the average expenditure is less (Campbell, 2021; Charles & Lundy, 2013).

Location efficiency is about more sustainable use of resources to cut down wasteful commuting and provide a vibrant environment for living. One crucial aspect of location efficiency is access to public transportation. Poor access in fringe areas often leads to a reliance on private vehicles for daily commuting, adding a significant capital expenditure to the household budget and increasing daily transportation costs (Banister, 1994; Currie & Senbergs, 2007). This not only raises the daily transportation cost but also increases the household’s total expenditure-to-income ratio (Viggers & Howden-Chapman, 2011). As a result, households residing in fringe areas, despite the lower housing rent, often incur higher overall living costs than what traditional economic theory suggests (Kellett et al., 2012). However, it is important to note that household location choices may not always be based solely on optimizing costs, as studies have shown that personal attitudes, beliefs, and lifestyle preferences can also play a role in their decision making, leading to higher expenditures on both housing and transportation (Deka, 2015).

From the above discussion, it is clear that owning to location efficiency, household economic status, and their subjective considerations, households make unequal expenditures on housing rent and commuting. This implies that households tend to compete for locations where they can meet their desired expenditure to income ratio. Based on the household residential location decisions the city has variations in population density, commuting distance, land price, house rent, and plot size. These aspects of the city ultimately define the neighbourhood morphology and livability of the households.

2.1. Using ABM as a simulation tool

Simulation can help to comprehend the emergence of city morphology as inhabitants engage with the built environment (Batty, 2007). Currently, agent-based models (ABM) are frequently used to simulate the behaviour of discrete decision-makers in an interactive setting. The simulations, performed by applying simple interactive rules between agents, can reveal the complexity of the system that arises from the collective behaviour of the agents. Furthermore, ABMs, owing to their dynamic nature, can provide insight into complex phenomena that are challenging to analyze using traditional statistical equilibrium models (Yen et al., 2019).

ABMs have been widely applied in various areas of urban planning, such as real estate modelling (Zhuge et al., 2016), transportation (Babakan & Taleai, 2015), economic development (Leao et al., 2017), segregation (Crooks, 2010), informal housing (Patel et al., 2012), disaster risk reduction (Crooks & Wise, 2013) and land use and transportation (Acheampong & Asabere, 2021). However, only a few studies have employed ABMs to simulate the change in residential location choices with variation in travel and housing cost. For example, Kulish et al. (2012) used ABMs to analyze how city morphology changes with changes in land use and transportation policies. Raux et al. (2014) used an ABM model to show the trade-off between commuting costs and rent costs and found results similar to those of traditional statistical equilibrium models. Yen et al. (2019) built an ABM inspired by traditional statistical models to simulate the density patterns under different income distributions, employment centres, transportation modes, and infrastructures.

In the above studies, the decision-making process for household relocation is centered on the maximization of utility through the minimization of rent and commuting costs. However, this approach fails to consider the expenditure levels of varying income households which they are willing to incur. Such a consideration is imperative as it determines the affordability of a location for a household. Location affordability serves as an income-based relative measure that informs the financial viability of a residential location to a household. The issue of affordability assumes greater significance since individuals tend to choose a location that not only provides them with increased access to resources and lower housing and travel costs but also meets their desired affordability threshold based on their income levels.
In light of this potential gap in the existing literature, this study aims to address the impact of varying levels of affordability on the urban form by constructing an Agent-Based Model (ABM). Specifically, the model will allow for the identification of the resulting urban form as the city becomes more or less affordable for different income groups. By incorporating a consideration of affordability into the decision-making process of agents, this study seeks to provide a more nuanced understanding of the interplay between affordability, residential location choices and urban form.

3. Model and parameters

3.1. Overview

The ABM model is built for a monocentric city in the NetLogo software (Wilensky, 1999). Households, represented as agents, are randomly placed throughout the city landscape and assigned a randomly generated income based on an income distribution. The agents use their income only for housing rent and commuting to the city centre. They are in one of two modes: searching or satisfied. At the start of the model, all agents are in search mode as they search for a location that minimizes their expenses. When an agent finds a suitable location, they become satisfied. The model ends when all agents are satisfied. A conceptual overview is shown in Fig. 1.

3.2. Design

The city is designed as a circular ring of radius of 14 units and a patch area of 10 units. The central patch is non-residential where all amenities and services are located, including agents’ place of work. Other than the centre, agents can occupy any patch. However, a patch can house a maximum of 10 agents, with each agent occupying 1 unit area. If a patch reaches its maximum capacity, it is no longer available for housing. Fig. 2 shows the city landscape. The number of agents (households) generated is set to half of the city’s total housing capacity, as calculated by Equation (1).

Every patch is characterized by two factors: patch density and proximity to the city centre. Patch density is calculated by adding the equally weighted ratios of satisfied agents in the patch and its Moore neighbourhood (8 neighbouring cells) to the total number of agents that the patch and its Moore neighbourhood can hold. The maximum number of agents in a Moore neighbourhood is 80 (10 agents per patch). Agents calculate their rent expenditure using Equations (2) and (3). Rent is assumed to be directly proportional to patch demand, expressed in terms of patch density. Commuting expenditure (Equation (4)) is expressed as a linear function of patch distance from the city centre and assumes same travel mode and fuel prices for all agents.

At the start of the model, agents are randomly placed on a patch and are in search mode. When they move to a patch, they calculate their expenditure-to-income ratio (EIR) using the patch density and distance from the city centre, as shown in Equation (5). Each agent on a particular patch incurs same expense on rent and commuting, but their EIR may vary due to differences in income.

\[
\text{Total agents (N)} = \frac{(\text{Total patches} \times 10)}{2}
\]

\[
\text{Patch Density (d)} = \frac{\text{Count of satisfied agents on the patch}}{2 \times 10} + \frac{\text{Count of satisfied agents on the patch’s neighbourhood}}{2 \times 80}
\]

\[
\text{Expenditure on rent (E_r)} = r \times d
\]

\[
\text{Expenditure on commuting (E_t)} = t \times \text{Patch distance from the city centre}
\]
Expenditure to Income Ratio (EIR) = \frac{(E + E_c)}{Income} \tag{5}

The housing rent coefficient is labelled as 'r' and the commuting coefficient is labelled as 't'. These coefficients can also be considered as the housing rent price per unit area and the commuting cost per unit distance, respectively.

### 3.3. Details and model calibration

The agents in this model are rational economic consumers who aim to minimize their expenditure-to-income ratio (EIR). The minimum EIR an agent can have is referred to as desired EIR. At the start of the model, all agents have a desired EIR of 0.1 and are in search mode. During each iteration, 10% of the agents in search mode are randomly selected to evaluate their current EIR. If an agent EIR is found to be equal to or lower than their desired EIR, they are labelled as satisfied. However, if the EIR is higher than their desired EIR, they search for a new location with an EIR equal to or lower than their desired EIR. Each agent can search for up to 10 locations in each iteration. If they fail to find a suitable location, their desired EIR is increased by 0.01 and they continue the search in future iterations. The model allows the unsatisfied agents to keep on searching in an unlimited manner, without having a relocation cost. The search process continues until all agents are satisfied.

The density of a patch and its surrounding neighbourhood changes as agents settle into or vacate the patch. This causes the housing rent on a patch to be proportional to its demand, making the expenditure on rent dynamic. However, the expenditure on commuting remains constant for a given patch. Only satisfied agents are counted in the calculation of patch density and only permanent residents are considered. Agents in search mode are temporarily located on a patch and are not counted in the density calculation.

We first run the standard model, where the agents’ income is generated using a random normal income distribution, with a mean income of 50,000 units and a standard deviation of 12,000. The minimum income is set at 10,000 units. Agents are divided into two groups based on their income: those with income higher than the mean income are classified as high income agents, and the rest are classified as low income agents. The input values for the standard model are outlined in Table 1. The results of the model help us understand how agent density and EIR vary with the city centre.

After running the standard model, four experiments are performed to evaluate the impact of different factors on the model. The first experiment involves changing the coefficients of rent and commuting to make them more or less expensive than the standard model. The second experiment involves varying income inequality levels using the beta distribution function of income and measuring the Gini coefficient. The third experiment involves randomly assigning two travel modes (public or private) to agents, with different commuting coefficients. The fourth experiment allows agents to occupy more than one unit of area on a patch. The results of these experiments are presented in section 4.

#### 3.3.1. Model calibration

To calibrate the model, we begin by randomly assigning income to each agent using a normal distribution with a mean income of 50,000 units per month. In a real-world scenario, income distribution curves are often positively skewed with a high proportion of households having income lower than the mean income. The model assumes income to be normally distributed in the standard model with low level of income inequality. The selection of the mean income has no impact on the outcome of the model as the model inputs the income to expenditure ratio rather than the absolute income. The value chosen for mean income is therefore arbitrary.

To set the values of rent and commuting coefficients, we consider the average household expenditures on these items from real-world scenarios. According to a recent OECD report on household expenditures (OECD, 2023), there is significant variation in mean expenditures on rent and commuting among countries. For instance, countries like Finland, UK, Japan, and France have households spending over 25% of their income on housing-related expenses and rent, while countries like Malta, Lithuania, and Turkey report expenditures below 15%. Commuting expenses tend to be more consistent across countries, with an average of around 10%. Based on these findings, we set the average expenditure on household rent and commuting to 20% and 10% of income, respectively. With a mean income of 50,000 units per month, this results in a mean expenditure of 10,000 units per month on rent and 5000 units per month on commuting. The coefficient of rent (r) can be calculated using Equation (3), as shown in Equation (6):

\[ r = \frac{\text{Expenditure on rent } (E_r)_{\text{mean}}}{d_{\text{mean}}} \tag{6} \]

Where \( d_{\text{mean}} \) denotes the fraction of residential area in the city. The ideal percentage of the land area allocated for residential purposes in a city can vary greatly depending on a number of factors, such as population density, land availability, infrastructure and transportation networks, local zoning laws and regulations, and cultural and economic factors. There is no universally agreed upon ideal percentage, as the needs and priorities of different cities can differ greatly. The value of the mean residential density \( d_{\text{mean}} \) in our model is based on the assumption that the ideal land use classification in a city should allocate 1/3rd of the area to green spaces, 1/3rd to industrial, infrastructure, and commercial uses, and the remaining 1/3rd to residential purposes. Using Equation (6), the rent coefficient (r) is calculated as 30000 per unit area.

Solving Equation (4), we get the expression for commuting coefficient (t) as shown in Equation (7):

\[ t = \frac{\text{Expenditure on commuting } (E_c)_{\text{mean}}}{\text{Patch distance from the city centre } d_{\text{mean}}} \tag{7} \]

As determined above, the mean expenditure on commuting \( (E_c)_{\text{mean}} \) is 5000 units and the mean patch distance from the city centre in our model is 7 units, which makes the value of the commuting coefficient (t) nearly equal to 700 per unit distance.

### 4. Results and analysis

#### 4.1. Standard model

This model tests the empirical relationship between variation in urban density with distance from the city centre in a monocentric form. The key output parameters are listed in Table 2. As shown in Fig. 3(a),

<table>
<thead>
<tr>
<th>Input variables</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean income</td>
<td>50000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean distance from city center</td>
<td>7.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total agent population</td>
<td>3965</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rent coefficient (r)</td>
<td>30000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commuting coefficient (t)</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum expenditure on rent</td>
<td>2000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum expenditure on commuting</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Output Variables</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>CV</th>
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</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.5</td>
<td>0.31</td>
<td>0.7</td>
<td>0.17</td>
</tr>
<tr>
<td>EIR</td>
<td>0.3</td>
<td>0.1</td>
<td>0.8</td>
<td>0.63</td>
</tr>
<tr>
<td>( E_r )</td>
<td>6978.69</td>
<td>2000</td>
<td>19125</td>
<td>0.6</td>
</tr>
<tr>
<td>( E_c )</td>
<td>6241.81</td>
<td>700</td>
<td>9800</td>
<td>0.38</td>
</tr>
<tr>
<td>Total Expenditure</td>
<td>13220.5</td>
<td>2700</td>
<td>21018.58</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Table 1: Input variables.

Table 2: Key output variables in the standard model.
the agents’ density decreases linearly as the distance from the city centre increases. The density coefficient of variation (CV) is 0.17, indicating a low variation in density with distance from the city centre. This leads to a low variation in rent as well, meaning that rent is less sensitive to the distance from the city centre. To minimize total expenditure, agents are more likely to reside close to the city centre to reduce commuting costs. The variation in income with distance from the city centre reveals that the high-income group tends to occupy the intermediate areas between the inner and outer regions of the city, while individuals with lower income settles within the inner and outer fringes of the city (Fig. 3(b)).

We now look at the variation in EIR with distance from the city centre. Fig. 3(c) demonstrates a linear increase in the EIR as the distance from the city centre increases, with a range of 0.23–0.35. This indicates that living costs, including rent and commuting expenses, increase as one moves away from the city centre. It’s noteworthy that the EIR differs between high and low income groups. On average, high income agents spend 40% of their income on rent and commuting, while low income individuals spend 17%, resulting in a 23% higher expenditure on these expenses for low income individuals as compared to high income ones, according to our model. We also notice how expenditure on rent declines and expenditure on commuting increases with increase in distance from the city centre (Fig. 3(d)). However, the decline in one is not completely offset by the increment in another, which makes the total expenditure to increase with increase in distance from the city centre.

### 4.2. Experiment 1: variation in the rent and commuting coefficient

In this part, we investigate how changing the rent and commuting coefficients affects location choice and city density. We use 9 combinations of rent and commuting coefficients, obtained by choosing coefficients 50% higher and lower than their standard values, and run the model to observe the variation in density pattern and location choices (as shown in Table 3). The density patterns are illustrated in Fig. 4(a). The lowest variation in density occurs when the rent coefficient is higher ($r_3$) and the commuting coefficient is lower ($t_1$) than their mean values. Conversely, the highest variation in density occurs when the rent coefficient is lower ($r_1$) and the commuting coefficient is higher ($t_2$) than their mean values.

When the commuting coefficient is low, increase in distance from the city centre has a smaller effect on commuting costs. If the commuting coefficient remains low and the rent coefficient is increased (combination $r_3t_1$), individuals strive to minimize their EIR by living in less dense areas, leading to urban sprawl. Conversely, if the rent coefficient is low, the cost of rent is less sensitive to changes in density. In this scenario, with a high commuting coefficient (combination $r_1t_3$), agents opt to live close to the city centre, causing overcrowding in inner city areas.

The spatial distribution of high and low income agents is also worth noticing. For the scenario with the lowest rent coefficient ($r_1$), two distinct income distribution patterns emerge. When the commuting coefficient is high ($t_3$), low income individuals live away from the city centre. Conversely, when the commuting coefficient is low ($t_1$), high income agents reside away from the city centre, creating patterns of economic segregation. This pattern repeats as the rent coefficient increases, although with less variation in income levels as a function of distance from the city centre, as seen in Fig. 4(b). This suggests that when commuting is more affordable, high income households prefer to live in outer city areas, spending less on rent, while low income households are pushed towards the city centre.

### 4.3. Experiment 2: Income inequality

In this experiment, we analyze the change in location choice and EIR for high and low income groups with a change in income inequality. Using beta distribution, we generate two income distributions having a Gini coefficient of 0.3 and 0.45. With increasing income inequality, the majority of agents’ income decreases, leading to an increase in the mean

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**Table 3**

<table>
<thead>
<tr>
<th>Combination</th>
<th>350</th>
<th>700</th>
<th>1100</th>
</tr>
</thead>
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<tr>
<td>15000</td>
<td>r1t1</td>
<td>r1t2</td>
<td>r1t3</td>
</tr>
<tr>
<td>30000</td>
<td>r2t1</td>
<td>r2t2</td>
<td>r2t3</td>
</tr>
<tr>
<td>45000</td>
<td>r3t1</td>
<td>r3t2</td>
<td>r3t3</td>
</tr>
</tbody>
</table>

Fig. 3. Variation in (a) density, (b) income, (c) EIR, and (d) expenditure with distance from the city center.
The average EIR rises from 0.3 to 0.6 as income inequality increases from 0.13 to 0.46. It is noteworthy that with an increase in income inequality, the EIR for the high-income group decreases while that of the low-income group increases (as shown in Fig. 5(a)). This indicates that high-income agents spend a smaller proportion of their income on rent and commuting when income inequality is high. Another interesting pattern observed is that as income inequality increases, the high income group is more likely to be located away from the city centre, while the low income group comes closer to the city centre, as shown in Fig. 5(b).

4.4. Experiment 3: Travel mode choice

In this experiment, we examine the impact of travel mode on residential location choice. Agents are randomly assigned to either public or private transportation modes. The commuting cost for private travel is fixed at $t_1 = 1000$, while the cost for public transportation, $t_2$, is varied from 700 to 100. At $t_2 = 700$, 500, and 300, a higher proportion of agents using public transportation reside outside the city centre (more than 10 units away) (see Fig. 6(a)). However, as $t_2$ decreases to 100, the trend changes and more number of agents using private transportation now locate in the outer city area, as shown in Fig. 6(b). This is a very interesting finding as it shows that making public transportation less and less expensive can significantly alter the residential location choice of commuters, drawing public transportation users closer to the city centre.

4.5. Experiment 4: occupied area

In our final experiment, we investigate the variation in household plot area with distance from the city centre. Similar to standard model, in this experiment also each patch has a total area of 10 units. However, now agents can occupy between one to two units of area per patch. As an agent moves to a patch, it determines the desired area to occupy based on its budget and the patch’s per unit rent, which is calculated as the rent coefficient multiplied by the patch density (Eq. (8)). If the patch has enough available space, the agent settles, otherwise it moves to another patch. After 10 attempts without finding a suitable patch, the agent increases its desired EIR by 0.01. To make the model more realistic, we set a minimum desired area of 1.5 units for high-income agents. The results show a linear increase in the mean area occupied by agents with increasing distance from the city centre.

\[
\text{Desired area} = \frac{(\text{Desired EIR} \times \text{Income} - \text{Expenditure on commuting})}{\text{Rent per unit area}}
\]

Studies have found that in monocentric cities, the average household plot size increases with distance from the city centre, due to lower density and rent. Our model results also show that when high-income agents prefer larger plots, agents’ income and the occupied area on a patch increases with increase in distance from the city center (as shown in Fig. 7). The change in income distribution from a bell-shaped curve in the standard model to a linear curve indicates that high-income agents shift from the intermediate zone to the outer area to occupy plots of bigger size. The mean plot size occupied by agents was found to be 1.38 units, exhibiting a 25% increase from the inner to the outer city. We also studied the impact of varying the rent and commuting coefficients on the occupied area however, the changes were found to be minimal.
5. Result validation and discussion

The paper performed an ABM simulation to study the impact of city affordability, measured in terms of expenditure on rent and commuting, on agents’ residential location choice. Through various experiments, the location choice of high and low-income agents and the resulting density pattern were analyzed. The validity of the model’s main results will now be assessed through a review of the relevant empirical literature.

The results of our standard model indicate a linear decline in city density with increasing distance from the city centre, which is a pattern commonly observed in many cities across the globe. For example, a spatiotemporal analysis of urban land densities by Xu et al. (2019) found this pattern in multiple cities in the USA, such as Minneapolis, Los Angeles, Houston, etc. Similar results have been reported for cities such as Manchester and Berlin (Dong et al., 2019).

The second observation from our model is a bell-shaped income curve as a function of distance from the city centre, suggesting that high-income households are more likely to reside in the city intermediate zone. This trend has been noted in several French cities, such as Paris and Lyon, and North American cities like New York and Chicago (Lemoy et al., 2013). Studies by François et al. (2011), Caubel (2005), and Glaeser et al. (2008) have also confirmed this pattern, where the city intermediate area is occupied by wealthy households while the inner and outer areas of the city are populated by lower income households.

The third observation pertains to the variation in the expenditure-to-income ratio (EIR) with distance from the city centre. Our model shows an EIR between 25% and 35%, which is a common benchmark for households (Gabriel et al., 2005), and an increase in EIR with increasing distance from the city centre. This suggests that housing affordability is higher in the city’s inner area compared to the outer area. Studies by Saberi et al. (2017) in Melbourne, Mattingly and Morrissey (2014) in Auckland and Kellett et al. (2012) in Adelaide have all reported similar results, where the suburbs are found to be less affordable than the inner city when housing and travel costs are considered. Our model also shows that the increase in travel costs with distance from the city centre is not offset by the decrease in housing rent, resulting in households in the outer areas having higher expenditures than those in the inner areas. This trend has also been noted by Liu et al. (2021) in their study of housing and transport costs in the Chicago metropolitan area, where they found that households in the inner city have lower housing and transportation costs compared to those outside the central city.

The results of experiment 1 in the paper provide valuable insights into the impact of transportation policies on urban development. The experiment shows that as the commuting cost increases, the city becomes more compact and less sprawl. This highlights the significance of transportation policies in shaping urban spatial planning. De Vos and Witlox (2013) conducted a study in the Flanders region of Belgium and found that cheap and convenient transportation has led to over-consumption of travel and urban sprawl, which can be addressed by increasing the cost of transportation, particularly for car users. Similarly, Lennox (2020) found that in cities in Australia, due to work-from-home policies, the frequency of travel has decreased, resulting in a flatter density gradient and urban sprawl. These findings further validate the results of experiment 1 and highlight the importance of considering transportation policies in urban development.

Another important observation from the results of experiment 1 is the increase in sprawl with the rise in rent prices. While many studies have explored the variation of property or housing prices with distance from the city centre, the impact of housing prices on location choices has received less attention. Only a few studies have examined this relationship empirically. For example, So et al. (2001) in their study of Iowa, USA found that a rise in housing costs decreases metropolitan residency and increases non-metropolitan residency. Ahrens and Lyons (2021) found that in the Dublin metropolitan area, an increase in rent is associated with an increase in commuting time, indicating increased demand for housing in suburban areas.

The results of experiment 2 indicate that with an increase in income inequality, high income agents tend to move from the middle part of the city center.
city to its outer area, while low income agents move towards the city’s inner and middle areas. This shows that income inequality exacerbates the segregation between high and low income groups. This is a crucial finding for inclusive urban development. The findings are supported by studies in the literature that show that income inequality is a significant factor in socio-economic segregation (Musterd et al., 2017). Tammuru et al. (2020) found a positive relationship between income inequality and residential segregation in European cities from the 1980s–2000s. Quillian and Lagrange (2016) also found that income segregation in US cities was driven by increasing income inequality, with low-income households concentrated in central cities and high-income households in the suburbs, consistent with the results of our model.

Result of experiment 3 reveals the relationship between location choices and mode of transportation. As previously mentioned, increasing the cost of transportation can lead to a more compact city. This experiment supports this idea, as agents using private transport, assumed to be more expensive than public transportation, are found to reside in the city centre while those using public transportation opt to live in the outer areas. A noteworthy observation is a shift in location preferences when the cost of public transportation drops significantly. In this scenario, agents using public transportation tend to reside in the city centre while those using private transportation move to the outer areas. This is a crucial finding that suggests that heavily subsidized public transportation can greatly influence the location choices of commuters. Currently, there is limited empirical research on the impact of public transport commuting costs on location choices, and as such, this finding from the model requires further validation.

Result of our final experiment shows that when agents are allowed to occupy larger plot areas, high-income agents shift from the city centre to the city’s outer areas, resulting in a linear increase in the average plot size with distance from the city centre. The desire for larger plots is one of the driving forces of suburbanization, as seen in many cities worldwide. A study by Kahn (2000) reported that cities in the USA, such as Chicago, Detroit, and New York, exhibit city-suburb land consumption differentials, with households occupying larger plots in city outer areas compared to the city centre. This is a crucial observation regarding the location choice of rich and poor households. By varying the maximum area a household can occupy, a city can influence the location preferences of high and low-income households.

6. Conclusion

In conclusion, the paper demonstrates that commuting and rental affordability play a crucial role in shaping the residential location choices of households, leading to a significant impact on urban morphology. Using an economic rational agent-based model of a hypothetical monocentric city, this study has made important observations that provide valuable policy directions for future research on the relationship between residential location choice, and affordability for different income groups. One of the main challenges in sustainable urbanization is to make cities more compact. Our model highlights the use of housing and transportation costs as a spatial policy tool to shape the urban form of a city. By increasing transportation costs and decreasing housing prices or rents, cities can promote compactness. At the same time, by optimizing rent and commuting prices, cities can become more affordable for residents and result in a more homogeneous density and income distribution.

Another issue in sustainable urbanization is income-wise segregation in cities. Our findings show that an increase in income inequality can lead to a more segregated city, with low-income households getting confined to city inner areas having low commuting costs but high rent, thereby increasing their overall household expenditure as a percentage of their income. To address this, cities exhibiting such location patterns need intervention in housing prices to make housing affordable for low-income groups residing near the city centre or job centres. Besides income inequality, our model also shows that plot size variability can contribute to the clustering of rich and poor households in cities, with rich households occupying larger plots in outer areas. Residential land policies that limit the maximum permissible plot area for households in a city can impact location choices and help reduce income-wise segregation.

The study has two important limitations. First, given that this study operates on the premise that agents are rational actors whose residential location choices are exclusively influenced by economic considerations, it would be prudent for subsequent investigations to incorporate the impact of non-economic and socio-cultural factors in shaping such decisions. Second, the model used in the study is designed for monocentric cities, which does not reflect the complexities of polycentric cities. Although monocentric urban forms can be seen in many cities around the world, the model can be improved to incorporate polycentric city designs.

CRediT roles

1. Aviral Marwal: Conceptualisation, Research design, Literature Review, Model formation, Analysis, and Discussion.
2. Elisabete Silva: Model formation, and Review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References


