Agent-based Housing Market Microsimulation for Integrated Land Use, Transportation, Environment Model System

The 2nd International Workshop on Agent-Based Mobility, Traffic and Transportation Models, Methodologies and Applications (ABMTRANS)

Agent-based housing market microsimulation for integrated land use, transportation, environment model system

Adam Rosenfield[a], Franco Chingcuanco[b], Eric J. Miller[c]*

ªDivision of Engineering Science, University of Toronto, 40 St. George Street, Toronto, ON, Canada, M5S 2E4
ᵇDept. of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139
ᶜDept. of Civil Engineering, University of Toronto, 35 St. George Street, Toronto, ON, Canada, M5S 1A4

Abstract

The Housing Market Evolutionary System (HoMES) is the updated housing market module for the Integrated Land Use, Transportation, Environment (ILUTE) model system. HoMES is a disaggregate, agent-based microsimulation of the owner-occupied housing market, with models for households' residential mobility decisions, location choices and valuations, the endogenous supply of housing by type and location, and the endogenous determination of sale prices and rents. The new model offers significant improvements over previous attempts by including a reformulated market clearing mechanism, market dependency on macro-economic conditions, and improved computational performance. A 100% synthesized population is validated against historical data for the Greater Toronto-Hamilton Area.

Keywords: microsimulation; market; disequilibrium; housing; integrated model; agent-based, ILUTE

1. Introduction

The ILUTE (Integrated Land Use, Transportation, Environment) model system is an agent-based microsimulation model that evolves an urban region's spatial form, demographics, travel behavior and economic structure over time. An operational prototype of ILUTE has been developed for the Greater Toronto-Hamilton Area (GTHA), simulating the evolution of a synthesized population over a twenty-year timespan (1986-2006).

The model system uses a dynamic population of agents (individuals, households, firms, etc.) that are endogenously evolved as the simulation progresses. Recently, there has been much progress towards developing the ILUTE Demographic Updating Module (I-DUM), which updates socio-demographic attributes throughout the simulation. I-DUM has received comprehensive testing, including historical validation over a twenty-year period [1]. Current efforts have focused on improving ILUTE's land use modeling component, specifically the owner-occupied housing market which consists of models for: households' residential mobility decisions, location choices and valuations [2] [3]; the endogenous supply of housing by type and location [4]; and the endogenous determination of sale prices and rents [5].

This component, in tandem with automobile ownership, labor force and firmographic models, serves as a key input for modeling transportation demand.

This paper presents the Housing Market Evolutionary System (HoMES), an updated implementation of ILUTE's housing market module. It is a complete microsimulation of urban housing market dynamics, with new models for market demand, price formation, as well as a bid-auction process on a fully disaggregate level. A framework of the new implementation is discussed in comparison to previous modeling efforts, and preliminary results are presented.

2. HoMES Overview

Various processes in ILUTE employ either a price-taking or price-formation market framework as a means of matching supply and demand agents [5]. The labor, marriage, and rental housing markets are all examples of price-taking markets, whereby prices are set prior to the market clearing process. In the case of marriage, no such 'price' exists, but the process can otherwise be modeled through the concept of supply and demand agents [6].

The owner-occupied housing market is, conversely, a price-formation market in which buyers bid the amounts they are willing to pay and sellers choose among the bids they receive. The housing market is updated in monthly time-steps, where individual dwelling units are listed on or withdrawn from the market and are cleared in an auction-type approach. However, ILUTE's housing market remains in a perpetual state of disequilibrium as there is no requirement for all supply and demand agents to clear at each step. Rather, homes may remain vacant should an acceptable bid not be received, and potential buyers may remain active in the market for several months at a time. Market dynamics are thus affected by the micro-level decisions of agents, as well as by the macroscopic impacts of excesses or deficiencies in either supply or demand.

Market entry for demand agents (i.e. households) arises from (a) the decision of an existing household to seek relocation, or (b) the formation of a new household seeking residence. Existing households may choose to enter the market by means of the *Residential Mobility Model*, while new households are formed as a result of the Demographic Updating Module. Either process results in a household entering the market demand pool. A binary choice model then determines whether the household will search in the rental or owner-occupied market.

Supply agents, namely dwellings, also enter the market through two different means: (a) the dwelling of an actively searching household may be put up on the market once that household decides to begin its search, or (b) a new dwelling may be constructed and listed on the market by its developer.
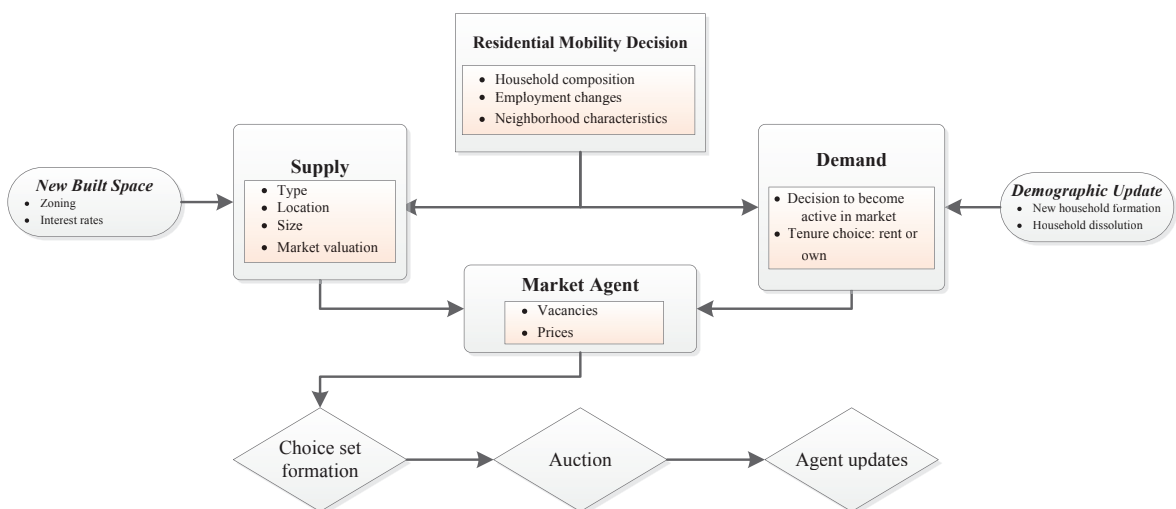

Figure 1. Framework of housing market supply, demand and clearing mechanisms.

Following market entry, the clearing process takes place whereby:
1. Sellers determine their asking prices based on their perceived value of their dwelling.
2. Buyers form their choice sets of potential dwellings.
3. Auctions take place for the active dwellings in the current time-step.

Agents may exit the market by either completing a successful transaction or withdrawing from the auction. In either case, the market agent will then assign the appropriate linkages and update the bidder and seller pools. An overview of market processes is shown in Figure 1.

3. Module Components

3.1. Market Entry

The determinants of residential mobility can be interpreted through the concept of residential *stressors* [7]. Various demographic and economic factors play a role in determining a household's relative satisfaction for its current dwelling against alternatives; this difference in perceived satisfaction is defined as stress. Residential stress evolves over the course of a household's tenure, with changing family composition and surrounding economic conditions resulting in push or pull forces towards moving. Life-cycle events occurring through I-DUM such as marriage, childbirth and divorce all contribute to increased likelihood of residential mobility and are thus important factors to be considered in a mobility model. A mixed-logit model developed by Habib [3] quantifies the effect of various residential stressors on a household's residential mobility decision. These stressors include: changes in employment (e.g., gains/losses/changes of jobs), changes in family composition (e.g., childbirth, moving out, aging), duration in current dwelling, and spatiotemporal economic data.

If a household decides to enter the housing market, the factors that trigger its mobility later become determinants of its choice set of dwelling alternatives. This forms an important linkage between residential stressors and location choice. This is of particular significance since the tenure decision (rental or owner-occupied housing), which directly impacts the supply and demand numbers for the owner-occupied market, has been shown to be dependent on a household's life-cycle phase, as well as the macroeconomic climate in which it resides [8]. Furthermore, this decision has also been found to be highly correlated to the previous tenure of a household: renters frequently choose to become homeowners, while the inverse is relatively uncommon. Other significant explanatory factors include household size and gross income, both of which are positively correlated to a higher propensity of homeownership.

3.2. Property Valuation

Upon market entry, each seller determines a price at which to list its house, with the asking price serving two purposes: firstly, it narrows the set of potential bidders, who have preconceived financial search constraints; secondly, it acts as a benchmark for dwelling utility calculations which form the basis of the market clearing mechanism. The asking price model has been updated to better incorporate the set of factors that have been found to affect list prices. These include physical dwelling attributes such as size and structural type. Also included are several macroeconomic indicators, namely unemployment, fuel prices and mortgage rates, all of which were found to be strong predictors of future housing market performance.

The most powerful predictor of future prices, however, is through historical trends. The new valuation model accounts for the results of previous endogenous housing market interactions, thus forming a longitudinal link between each month's market activity. Aggregate market trends such as supply-demand imbalances will affect prices, as will an individual dwelling's market history. For example, a home that has lingered on the market for several months will tend to drop its asking price. By integrating the dwelling valuation model within the ILUTE system, the interdependencies between economic growth and housing market performance can be captured while allowing for exogenous macroeconomic indicators to influence market dynamics.

3.3. Location Choice

While the seller seeks to maximize profit, the homebuyer is seeking to maximize his or her utility attained by purchasing a new home. Although the buyer is seeking an optimal solution (i.e., the "perfect home"), various constraints preclude the searcher from considering all possible dwelling alternatives. Thus, a confined choice set forms

the sample space for each potential transaction. In this sense, buyers and sellers have a myopic approach to the market whereby only limited information about each agent is known to others. Prospective buyers only have detailed information on dwellings in their choice set, and sellers are similarly unaware of the actions of other sellers. As such, it is imperative that the choice set formation model accurately represent the preferences of each household as all subsequent market clearing processes depend on an appropriate selection of homes.

Of all the mechanics of the housing market, the choice set problem is possibly the most difficult to model, owing to the inherent subjectivity associated with how households choose potential homes. Young [9] proposed an *elimination-by-aspects* (EBA) approach in which the choice set is confined through a decision tree, where a household's most important attributes are first used to eliminate alternatives, followed by successively less important traits. This is in contrast to traditional residential location models, which assume a trade-off between the agent's satisfaction for one attribute and its satisfaction for another [10]. An EBA approach simplifies the choice set restriction while more closely capturing the decision process of individuals who seldom consider all attributes of a an alternative simultaneously when confining their search [11].

The HoMES choice set formation is based on an EBA algorithm, using search preferences revealed by a 1998 Residential Search Survey [12]. Up to twelve dwellings are considered each month, reflecting observed search tendencies. Dwelling alternatives are first filtered by tenure, with the assumption that dwelling tenure remains fixed and no tenure conversion or subletting occurs. Alternatives are then narrowed down by structural type (detached, semi-detached, row house, low/high rise apartment) using a multinomial logit with household income, size, and previous dwelling characteristics as predictor variables.

Following choice set restriction by structural type, the searcher will only consider dwellings whose size matches the needs of the household, based on the results of the residential mobility model (i.e. expanding households looking to upsize). The final restriction of alternatives is by asking price, which scopes down the list of potential dwellings significantly. Historical patterns provide a range of typical price-to-income ratios for homebuyers. In all, these restrictions result in a choice set small enough to be manageable for the potential homebuyer.

3.4. Auction Process

The final step in the HoMES model is market clearing. The previous version, as described in Farooq and Miller [5], expresses a buyer's bid for a house through the probability that the house is sold to this buyer at a given price. A price is determined through a search procedure that clears this dwelling unit. Due to this probabilistic formulation, however, the previous approach has some limitations. For instance, the market fails to clear whenever a bidder only has one house in his or her choice set since that probability will always be one at any price. To overcome this limitation, the new version works on the basis of individual bids based on households' willingness-to-pay (WTP) for dwellings in their choice sets. Under a random utility framework [13], the attractiveness of dwelling j to buyer i can be expressed as a utility composed of three terms: a price utility term (V_{ij}^r), a non-price utility term (V_{ij}^R) based on dwelling characteristics, and an error term (ε_{ij}) accounting for differences between observed and predicted choice behavior. Dwelling utility U_{ij} is the sum of these terms:

$$U_{ij} = V_{ij}^r + V_{ij}^R + \varepsilon_{ij} \tag{1}$$

where $V_{ij}^r = \gamma R_{ij}$, where $R_{ij} = \log(price_{ij})$, weighted by a parameter γ;
$V_{ij}^R = \boldsymbol{\beta} \cdot \boldsymbol{X}_{ij}$, where $\boldsymbol{X}_{ij}$ is a vector of dwelling attributes weighted by a vector of parameters $\boldsymbol{\beta}$; and
ε_{ij} is a Type I Extreme Value distributed error term.

The total utility is therefore:

$$U_{ij} = \gamma R_{ij} + \boldsymbol{\beta} \cdot \boldsymbol{X}_{ij} + \varepsilon_{ij} \tag{2}$$

Each active household i has a choice set of dwellings (C_i), and each active dwelling has a set of bidders (B_j). In the previous market clearing formulation [5], a micro-equilibrium constraint was imposed whereby a dwelling's selling price is varied until certain conditions are met (probability sums across buyers and sellers both equal one). This algorithm was found to break down when bidder sets are too small or too large. If a dwelling has very few bidders, the transaction price may be forced to drop significantly to achieve a unit sum of probabilities. Conversely, for a dwelling

with many interested homebuyers, the price may be inflated beyond reasonable values. Furthermore, such an algorithm only determines a transaction price, with the winning bidder chosen randomly from amongst the bidder set.

A new clearing mechanism has been implemented that, rather than imposing a micro-equilibrium, auctions off each dwelling using bidders' WTP. Bidders first determine their non-price utility for each dwelling in their choice set:

$$\tilde{U}_{ij} = \boldsymbol{\beta} \cdot \boldsymbol{X}_{ij} + \varepsilon_{ij} \tag{3}$$

$\boldsymbol{\beta} \cdot \boldsymbol{X}_{ij}$ is evaluated based on the attributes of the dwelling unit and the parameters found in Habib [14]. The random error term ε_{ij} is simulated by drawing from a Type 1 Extreme Value distribution. Then, for each active dwelling j with bidder set B_j, members of the bidder set determine the highest utility they can achieve for all homes in their choice set *other* than the current dwelling j:

$$U_{ij_{max}} = \max_{j' \neq j \in C_i} (\gamma Ask_{j'} + \tilde{U}_{ij'}) \tag{4}$$

where $Ask_{j'}$ is the dwelling's asking price. $U_{ij_{max}}$ gives the maximum utility bidder i can obtain from the other alternatives in its choice set and therefore sets bidder i's WTP for all other dwellings in its choice set. Herein lies the importance of the asking prices, as they reflect the market's valuation of each home and are a necessary means of comparison between choice set alternatives. Household i, with a maximum utility of $U_{ij_{max}}$, can bid a certain amount on dwelling j to achieve that same utility. Substituting equations (3) and (4) into (2), the price the bidder is willing to pay for this utility is therefore

$$R_{ij} = \left(U_{ij_{max}} - \tilde{U}_{ij} \right) / \gamma \tag{5}$$

and reflects the bidder's relative preference to all other dwellings in its choice set.

Once all bids have been tendered, the seller evaluates its options and may choose to either sell to the highest bidder, or reject all offers if none are deemed acceptable. If the highest bidder's offer is accepted, the dwelling is transacted in a Vickrey auction whereby the transaction price is equal to the second highest bid (plus a dollar) which most closely reflects the true market value of the home [15]. This bid-auction process results in a more realistic simulation of market transactions with respect to asking and transaction prices as well as the duration of agents' market activity. It further improves the dependence of market clearing on macroeconomic and land use trends as manifested in supply-demand interactions.
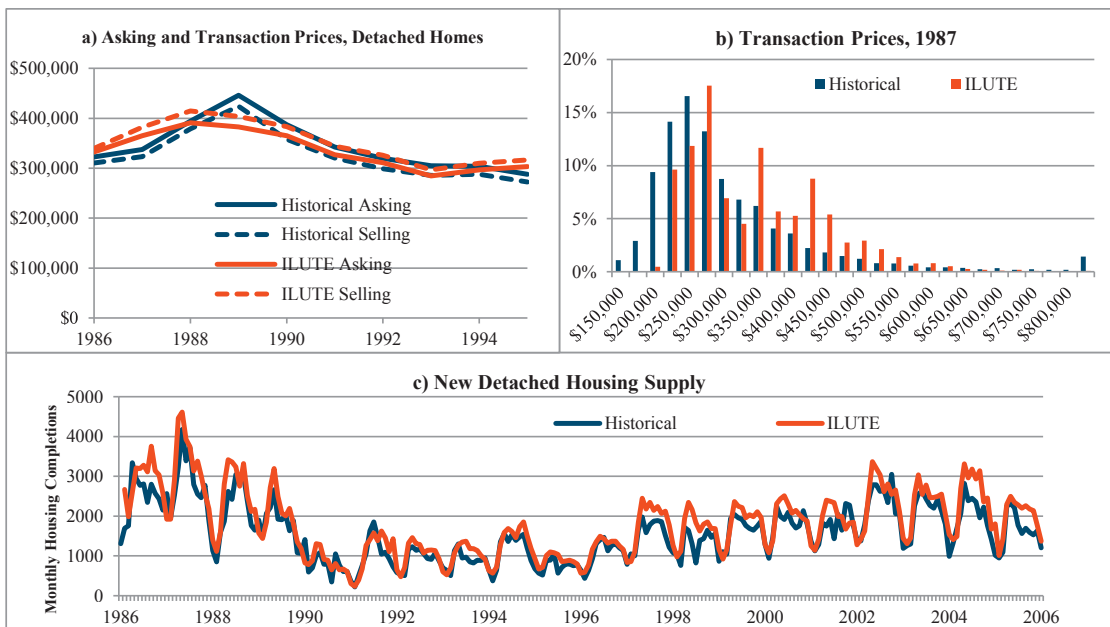

Figure 2. HoMES validation against TREB and CMHC data.

4. Model Performance and Validation

The HoMES module of ILUTE has been implemented in the C# .NET framework. Parallelization of many of the computationally expensive algorithms has resulted in starkly improved performance; run-time for a twenty year simulation of the GTHA's 1.5 million households has dropped from the order of days to approximately one hour as a result of streamlined and parallelized code. Efforts are underway to comprehensively test and validate HoMES using data from the Toronto Real Estate Board (TREB) and the Canadian Mortgage and Housing Corporation (CMHC). Using a 100% population sample, the model's average asking and selling prices follow historical trends (see Figure 2a), though ILUTE selling prices tend to be slightly higher than asking, contrary to conventional market dynamics. Figure 2b compares cross-sectional distributions of transaction prices in 1987, and is indicative of slight systematic over-prediction. Supply of new detached houses, illustrated in Figure 2c, generally exhibits strong correspondence with CMHC data. Results for other types of housing show similar temporal trends; further results on housing supply can be found in Farooq and Miller [5]. While preliminary validation results are promising, challenges remain to attribute model inaccuracies to the appropriate sub-component. For example, skewed distributions of transaction prices may be a product of the bid-auction process, asking price formation, improper residential mobility determination or even population demographics. Such interdependencies are reflective of the integrated modeling paradigm and present challenges in model calibration. Understanding and resolving these discrepancies is the subject of current analysis.

5. Conclusion

This paper has presented an agent-based implementation of urban housing market dynamics as part of the ILUTE model system. HoMES introduces some key features that offer marked improvement over previous models. These include: better integration among housing market sub-models, such as predictors of residential mobility becoming determinants of choice set formation; explicit modeling of the residential tenure decision; an improved asking price model more sensitive to endogenous micro and macro-economic factors; a willingness-to-pay framework of market clearing using a bid-auction process; and finally, a streamlined technical implementation with performance capabilities to rapidly execute full-population simulations. Future work remains to be done to further incorporate the spatial attributes of location choice into the land use model. Furthermore, completed implementation of a rental housing market simulation would complete the HoMES framework. Commercial and industrial land use models are also a key necessity in modeling firmographic and labor force dynamics, and remain as priorities for the ILUTE modeling team.

References

[1]   Chingcuanco, F. and Miller, E.J. Demographic Microsimulation Model for Integrated Land Use, Transportation, and Environment Model System. In *92nd Annual Meeting of the Transportation Research Board* (Washington, D.C. 2013).

[2]   Habib, M.A. and Miller, E.J. Influence of Transportation Access and Market Dynamics on Property Values: Multilevel Spatio-Temporal Models of Housing Price. *Transportation Research Record: Journal of the Transportation Research Board* (2008), 2076: 188-191.

[3]   Habib, M.A. and Miller, E.J. Reference-Dependent Residential Location Choice Model within a Relocation Context. *Transportation Research Record, Journal of the Transportation Research Board* (2009), 2133: 56-63.

[4]   Haider, M. and Miller, E.J. Modelling location choices of housing builders in the Greater Toronto Area. *Transportation Research Record*, 1898 (2004), 148-156.

[5]   Farooq, B. and Miller, E.J. Towards integrated land use and transportation: A dynamic disequilibrium based microsimulation. *Transportation Research Part A: Policy and Practice*, 46, 7 (2012), 1030-1053.

[6]   Miller, E.J., Chingcuanco, F., Farooq, B., Habib, K.M.N., Habib, M.A., and McElroy, D. Development of an operational integrated urban model system, volume IV: Demographic and labour market updating. *University of Toronto* (2008).

[7]   Rossi, P. *Why families move: A study in the social psychology of urban residential mobility*. Free Press, Glencoe, Illinois, 1955.

[8]   Henderson, J. V. and Ioannides, Y. M. A model of housing tenure choice. *The American Economic Review*, 73, 1 (1983), 98-113.

[9]   Young, W. A non-tradeoff decision making model of residential location choice. *Transportation Research*, 18A (1984), 1-11.

[10]   Lerman, S. R. *A disaggregate behavioural model of urban mobility decisions*. PhD Thesis, Cambridge, 1975.

[11]   Michelson, W. *Environmental choice, human behaviour, and residential satisfaction*. Oxford University Press, New York, 1977.

[12]   Pushkar, A. O. *Modelling household residential search processes*. MASc Thesis, Toronto, 1998.

[13]   McFadden, D. Conditional logit analysis of qualitative choice behaviour. *Frontiers in Econometrics* (1974), 105-142.

[14]   Habib, M.A. *Microsimulating residential mobility and location choice processes within an integrated land use and transportation modelling system*. PhD Thesis, Toronto, 2009.

[15]   Vickrey, W. Counterspeculation, Auctions, and Competitive Sealed Tenders. *The Journal of Finance*, 16, 1 (1961), 8-37.