Computers, Environment and Urban Systems 69 (2018) 87–103

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/ceus

Microsimulation of life-stage transitions and residential location transitions within a life-oriented integrated urban modeling system

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A R T I C L E I N F O

Keywords:
Integrated urban model
Microsimulation
Life-stage transition
Residential location transition
Multi-domain interaction and process orientation
Population synthesis

A B S T R A C T

This paper presents microsimulation of life-stage transitions and residential location transition processes within a life-oriented agent-based integrated Transport Land Use and Energy (iTLE) modeling system. The iTLE assumes that individuals and households are the agents, and parcels are the objects. It is conceptualized following the life-course perspectives and theories to address the evolution of multi-domain decision interactions over the life-course of the agents. Residential location is simulated as a two-stage process of residential mobility, and location choice. Life-stage simulation includes aging, death, birth, out-migration, in-migration, and household formation. The iTLE is implemented at a yearly time-step from 2006 to 2021 for Halifax, Canada. A 100% synthetic population is generated for the base year 2006, which shows a SRMSE value of 0.37 and APE measures of less than 5% for 89% of the DAs. The simulation results are validated with the 2011 Census information. The validation results suggest that the iTLE generates reasonably satisfactory population estimates. For example, around 52% of the DAs show an APE value of less than 30%, and 37% of the DAs show a difference in the number of households of less than ± 50. The predicted results regarding the spatio-temporal evolution of Halifax suggests an increase of around 14% population in 2021 compared to 2007. Younger population residing closer to the CBD are predicted to be more frequent movers than older population residing farther away from the CBD. Higher proportions of the households are predicted in the locations within 25 km from the CBD over the years. Proportion of households in these high density neighborhoods are predicted to increase from 68% in 2007 to 71% in 2021. In 2021, a higher density of single person households are predicted in the urban core. Density is predicted to be more variable and skewed towards suburban neighborhoods as household composition changes through marriage and child birth.

1. Introduction

The development of integrated urban models has emerged from the need to mimic the dynamics of the two-way interaction between land uses and travel activities. Integrated urban models simulate populations' decision processes to predict the evolution of urban form and transportation system over time and space. One of the crucial components of an integrated urban model is the long-term decision processes such as location choice (Habib, 2009), which predicts the spatial configuration of an urban region. Long-term decisions have a dynamic nature, since decisions of where to live, and where to work interacts with medium-term and short-term decisions of whether or not to own a vehicle, and what mode to choose. Moreover, long-term decisions of where to live evolve over the life-course as well as interact with life-stage transitions; for instance, birth of a child influences residential location choices (Strom, 2010). In addition, long-term decisions such as location choice has an inherent process orientation. For example, residential location is a process of decision to move (i.e. mobility) and location choice. Furthermore, there is an inter-generational effect, as younger population and older adults of this generation show different behavior than that of earlier generations (Garikapati, Pendyala, Eric, Patricia, & Noreen, 2016; Lin et al., 2014). Such dynamic behavior of the population posits a challenge for planning healthy communities as well as offering equitable and sustainable travel opportunities for people at different life-stages. To effectively evaluate land use and transport policies, integrated urban models need to be responsive to the decision dynamics across the agents' life-stages, starting with the long-term decisions, and life-stage transitions.

With the motivation to mimic the multi-domain decision interactions, life-course dynamics, and process orientation of the decisions,

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https://doi.org/10.1016/j.compenvurbsys.2018.01.003
Received 19 October 2017; Received in revised form 5 January 2018; Accepted 6 January 2018
Available online 17 January 2018
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this paper micro-simulates residential location and life-stage transition processes within a life-oriented integrated Transport Land Use and Energy (iTLE) modeling system. The iTLE is an agent-based urban system model that follows life-course perspectives and theories (also known as life history-oriented approach) (Chatterjee & Scheiner, 2015). Life-course perspective focuses on how transitions along the life-time and interactions among decisions taken at different domains along the life-time shape individuals' choices and behavior (Chatterjee & Scheiner, 2015; Zhang, 2015; Zhang, 2017). The iTLE model adopts the concept of life-course perspective in developing the micro-modeling structures and computational procedures to simulate agents' decisions longitudinally at each simulation time-step along their life-course. The iTLE software operates at the finest spatial unit of parcel. A proto-type version of the model is implemented for the Halifax Regional Municipality (HRM), Canada. This paper presents the conceptual framework of iTLE, and the simulation results of life-stage transitions and residential location transitions. Specifically, this paper offers a full-scale validation of the model and reports results regarding the spatio-temporal evolution of HRM in terms of its population demographics and spatial distribution, and demographic configuration of the neighborhoods. In addition, this study presents results of a parcel-level population synthesis procedure, which feeds baseline information to the simulation engine of the iTLE.

The organization of remainder of the paper is as follows: the next section provides a review of relevant literatures and identifies the contributions of this study, followed by a discussion on the conceptual framework of the iTLE model. The subsequent section describes the implementation of life-stage transition and residential location transition modules within a proto-type iTLE model. In this section, a brief description of the data sources, methods of microsimulation processes, validation, and simulation results are presented. Finally, a summary of contributions along with future works are discussed in the conclusion section.

2. Literature review

For the past fifty years, researchers have devoted tremendous effort in developing integrated urban models. Based on the operating principles, currently available integrated urban models can be subdivided into five categories: (1) Economic Activity-based Models: PECAS (Hunt & Abraham, 2003), MEPLAN (Echenique, Crowther, & Lindsay, 1969), and TRANUS (de la Berra, Perez, & Vera, 1984); (2) Market Principle Models: ILUTE (Salvini & Miller, 2005), CPHMM (Anas & Arnott, 1993), and SelfSim (Zhuge, Shao, Gao, Dong, & Zhang, 2016); (3) Quasi Market-based Models: UrbanSim (Waddell, 2002), SimTRAVEL (Pendyala et al., 2012), and ILUMASS (Wagner & Wegener, 2007); (4) Hybrid Models of Heuristic, Utility, and Market Principles: PUMA (Ettema, de Jong, Timmermans, & Bakema, 2007), CEMUS (Eluru et al., 2008), SimDELTA (Simmonds, Christodoulou, Feldman, & McDonald, 2011), and RAMBLAS (Veldhuisen, Timmermans, & Kapoen, 2005); and (5) Emerging Complex System Models: SimMobility (Adnan et al., 2016), POLARIS (Auld et al., 2016), and iTEAM (Ghauche, 2010); among many others. Past literature suggests that considerable progress has been made in developing fundamental theories to understand the dynamic evolution of urban processes, and translating those theories into the modeling methodologies and simulation framework for improved abstraction of the urban system. Integrated urban models are evolving from initial aggregate-level models that follow the economic activity theory to more recent, emerging complex modeling systems that capture greater behavior at the most disaggregate-levels (i.e. individuals, households).

The majority of the urban models developed prior to the mid-1990s take an aggregate modeling approach. One of the major limitations of the aggregate approach is that the models account for collective effects of a fairly large spatial zone, which leads to insufficient representation of disaggregate-level behavioral dynamics and may result in averaged, poor estimation and forecasting of the urban system (Ettema et al., 2007). Such limitations of the earlier models have led to the development of agent-based microsimulation models, such as ILUTE, UrbanSim, PUMA, ILUMASS, and SimMobility. An agent-based approach offers the opportunity and flexibility to represent agents' greater behavior through micro-behavioral models for different decision-making processes. Particularly, it is essential to simulate the location processes with sufficient details, which are the skeletal elements for land use representation within integrated urban models (Eluru et al., 2008; Ettema et al., 2007; Habib, 2009; Waddell, 2010).

A wide array of concepts is used to represent agents' behavior regarding residential location choices. For instance, in ILUTE, residential location choice is conceptualized to take place in the housing market as a three stage process: mobility, search, and bid (Habib, 2009). Mobility refers to the decision of becoming active in the market, then the active households undertake a search process to identify potential dwellings that are available in the housing market, and finally a bid is made on a dwelling based on its desirability and asking price. In UrbanSim, residential location choice is simulated in two stages: a rule-based model for mobility decisions, and a multinomial logit model for location choices (Waddell et al., 2003). Following the simulation of location choice, the housing market is cleared by undertaking a capacity constrained algorithm using a first come first serve technique of allocating dwellings to the households (Waddell, 2010). In PUMA, residential location choice is a sequence of three consecutive decisions: search, decision to move, and location choice (Ettema et al., 2007). The search and decision to move follows a binary logit modeling approach, and the location choice is determined by a multinomial logit model. Allocation of location is made through the interaction between buyers and sellers in the market on the basis of maximum lifetime utility. In the case of CEMUS, first a mobility model is developed using binary logit modeling technique, and then a location choice model is developed using multinomial logit modeling technique (Eluru et al., 2008).

The majority of the above mentioned micro-behavioral models developed to simulate location choice processes are estimated based on the characteristics of the locations (i.e. accessibility and neighborhood), and its' interactions with households' socio-demographic characteristics; which limits their ability to address the life-trajectory dynamics of the phenomenon. In reality, long-term decisions, such as choice of residential location is a dynamic decision taken over the life-course of the households as they move from one location to another during their life-time (Chen & Lin, 2011Habib & Miller, 2009). The choice of location interacts with decisions across life-domains, such as vehicle ownership, mode choice, and life-stage transitions (i.e. birth of a child, death of a member, retirement) occurring at different stages of the life-time (Strom, 2010; Kim, Horner, & Marans, 2005; Oakil, Ettema, Arentze, & Timmermans, 2014). In fact, long-term decisions are itself critical transitions or events in the life-time of an individual or household. Hence, agents' life-trajectory dynamics need to be addressed within the modeling and simulation frameworks of long-term decision processes.

To address the life-trajectory dynamics, individuals' life-stages have to be simulated. A large body of literature exists on population demographic microsimulation (Gribble, 2000; King, Baekgaard, & Robinson, 1999; Nelissen, 1995; Orcutt et al., 1976); however, integrated urban models have not sufficiently addressed life-stage transition processes. Limited urban models such as ILUTE, PUMA, and CEMUS, have the demographic updating component, which mostly follows a heuristic modeling approach. The demographic updating component of ILUTE simulates the following events: birth, death, marriage, divorce, move out, driver's license, out migration, and in-migration (Chingcuanco & Miller, 2013). The demographic events simulated within PUMA includes: aging, birth, marriage, divorce, and leave parental home (Ettema et al., 2007). The population update component of CEMUS involves: birth, death, divorce, emigration, and immigration, among others (Eluru et al., 2008). However, establishing the interactions

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