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An Agent-Based Modeling approach for sustainable urban planning from land use and public transit perspectives

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ABSTRACT

Urbanism is a challenging topic in the world, which has resulted in several land-use and transportation issues in urban environments. To address these issues, urban planners follow integrated planning approaches that are more compatible with sustainable development objectives. Transit-Oriented Development (TOD) is widely recognized as one of the most feasible and comprehensive sustainable planning approaches. In this research, a three-step TOD-based method was developed for sustainable urban planning in the central region of Tehran. First, a measurable index was developed to assess public transit infrastructure (PTI) and TOD levels in the study area. At the second step, which was the focus of the research, an Agent-Based Modeling (ABM) approach was used to make a balance between TOD and PTI levels. ABM is a bottom-up approach that can solve spatial problems and can be integrated with top-down policies and spatial analysis tools. Finally, the performance of the model was evaluated by conducting several statistical, visual and empirical assessments using Tehran municipality's reference data. These assessments confirmed the efficiency and feasibility of the model.

1. Introduction

Nowadays, a majority of the world's population lives in cities (Chawla, 2016); therefore, there is a substantial need for the effective management of limited resources in cities. A comprehensive planning approach plays an underpinning role in the efficient and smart management of limited resources in urban environments. Without having such a comprehensive urban planning strategy, cities will face with critical issues such as urban sprawl, inappropriate distribution of facilities, environmental pollutions, traffic congestion, and insufficient urban infrastructures such as public transit system (Ewing, Tian, Lyons, & Terzano, 2017; Shirzadi Babakan, Alimohammadi, & Taleai, 2015; Wey, 2015; Wey, Zhang, & Chang, 2016; Widyahari & Indradjati, 2015). To tackle these issues, the urban planning strategy should cover both the land use and transportation parts. These parts have a mutual relationship; therefore, many researchers have developed Integrated Land-Use and Transportation (ILUT) models (Shirzadi Babakan & Alimohammadi, 2016; Waddell, Ulfarsson, Franklin, & Lobb, 2007; Wegener, 2011; Yim, Wong, Chen, Wong, & Lam, 2011).

A successful ILUT model from the perspective of developing public transit system is Transit-Oriented Development (TOD) model. This model encourages non-motorized transportation modes of walking and cycling for short trips and public transport modes including bus and subway for longer trips. Thus, the implementation of this model will lead to the creation of lively, healthy, and pedestrian-friendly communities and neighborhoods (Binglei & Chuan, 2013; Cervero, 2004; Cervero, Guerra, & Al, 2017; Evans, Pratt, Stryker, & Kuzmyak, 2007; Galelo, Ribeiro, & Martinez, 2014; Singh, Fard, Zuidgeest, Brussel, & van Maarseveen, 2014; Wey, 2015; Wey et al., 2016).

In recent years, different definitions of TOD have been proposed in the literature (Nasri & Zhang, 2014). Nevertheless, there are some common factors in most of these definitions such as developing mixed-use area with high density and diversity, and being convenient for walking and cycling in 2000 ft around the public transit stations (Belzer & Autler, 2002; Calthorpe, 1993; Cervero, Ferrell, & Murphy, 2002; Kwon, 2015; Ratner & Goetz, 2013; Wey, 2015; Wey et al., 2016). In addition, researchers have adopted the TOD concept in the urban planning. The TOD planning approach covers all the areas, and not just the areas around the public transit stations (Cervero, 2013; Cervero & Dai, 2014; Evans et al., 2007; Motieyan & Mesgari, 2017a, 2017b; Singh et al., 2014). In this study, we developed a novel agent-based modeling approach based on the concept of TOD planning to manage land-use activities as well as the public transit system. This planning requires a robust method that can handle top-down and bottom-up procedures.

1.1. Literature review

ILUT models have been widely used in various research and

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development investigations since the 1960s. Earlier versions were not successful because of their theoretical and technical limitations. However, their recent versions have been significantly improved by using disaggregated micro-simulation methods (Babakan & Taleai, 2015; Shirzadi Babakan & Alimohammadi, 2016; Wegener, 2011). One of the most practical and comprehensive ILUT models is UrbanSim (Waddell et al., 2003). The focus of this model is on tracking the residential location of individual households, distributing employments, and identifying travel patterns according to households' socioeconomic attributes, environmental characteristics, and accessibility levels (Waddell et al., 2007). However, the UrbanSim model has the following drawbacks: 1) Allocating a household or a job in a location depends on many attributes that the model cannot certainly consider; 2) It cannot create the sustainable lively and pedestrian-friendly neighborhoods; 3) The recent concerns of urban planning, including urban sprawl and smart growth, are not considered; 4) This model has some technical problems in terms of huge data need, computing time, and stochastic variation. These limitations have persuaded researchers to build their models regarding conceptual, spatial, and temporal requirements (Kakaraparthi & Kockelman, 2010; Wegener, 2011). On the other hand, TOD planning is a sustainable ILUT planning approach that considers many factors such as smart growth, urban sprawl, land-use planning, public transport planning, attracting private investment, optimizing landscape and urban design, and developing all the areas without considering who wants to live there. In TOD planning, these factors are considered to ensure sustainable urban planning and social justice in cities.

In many studies, the TOD concept has been employed to select the best scenarios for enhancing public transit services (Wey, 2015; Wey et al., 2016). However, there are limited studies investigating the TOD planning throughout an entire urban area using a spatial index (Motieyan & Mesgari, 2017a, 2017b; Singh et al., 2014). Singh et al. (2014), first developed a spatial TOD index to evaluate TOD levels in the entire urban area; then they used a clustering method to determine areas with high TOD levels for developing public transit stations. Although their study was a novel contribution to the TOD planning, their proposed approach had the following weaknesses: 1) They did not consider comprehensive and efficient indicators to develop a TOD index. 2) An effective aggregation method was not used to aggregate indicators and criteria. 3) They did not suggest any solution for improving TOD levels in the region, especially in the areas with potentials for developing public transit services. These weaknesses can be addressed by several ameliorative actions such as increasing density, diversity, and accessibility. These actions have different consequences and thereby it is essential to develop a method to assess their consequences and to select the optimum actions.

1.2. Research contribution and objectives

The main contribution of this study is the development of a novel agent-based method that helps in making ameliorative decisions with regard to the TOD level, public transit infrastructure (PTI) level, and upstream policies. The proposed method uses both bottom-up and top-down procedures to consider all criteria and policies required for the amelioration. According to the authors' knowledge, such a comprehensive method for TOD planning has not yet been presented. This method would potentially help urban planners to make smarter, better, and more comprehensive decisions in an urban area.

In this study, we pursued several objectives. First, to develop a comprehensive, efficient and practical method, it was necessary to extend the indicators considered in existing TOD models. In comparison with Singh et al. (2014), we considered new indicators such as administrative density, accessibility, street connectivity, street design, population categories, household size, educational level, facility level, trip generation, and route and service performance. Based on our study, these indicators play important roles in urban planning. The second objective was to use an effective aggregation method to aggregate the indicators, as the previous models (e.g., Singh et al. (2014)) did not use an appropriate aggregation method. The third objective was to develop an agent-based model for evaluating urban areas from different perspectives, and for making suitable decisions based on the evaluations and upstream policies. Finally, to verify the viability of the proposed method, it was essential to assess the consequences of the decisions using some reference data.

2. Materials

2.1. Study area and data

In this study, the proposed method is implemented in the 7th municipal region of Tehran, the capital of Iran. There are several reasons for selecting this region as the case study: 1) This region is a high-density area with different land uses; therefore, land use planning is essential for the region; 2) Trip generation and trip attraction levels are high in this region; thus, the public transportation plays a key role in the region. Crossing all subway lines and two major BRT lines within the region is a strong witness for this key role. The 7th region is divided into five districts and twenty-two neighborhoods. Additionally, total population and area of the region are around 300,000 individuals and 1536 ha, respectively. Fig. 1 shows the 7th region and its neighborhoods.

In this study, to develop the proposed method, data sets with the following descriptions are used.

1) Maps of regions, neighborhoods, and parcels of Tehran with their characteristics such as area and land use; and street map with the attributes of street type and pavement type
2) Demographic data at the neighborhood scale, such as educational level, professional status, age, and household size.
3) Public transit map including the location of routes and stations with their attributes such as capacity, average speed, and frequency of services.

2.2. TOD and PTI concepts

TOD is a fundamental concept in urban planning and smart growth. Therefore, different studies have investigated this concept from different points of view. Calthorpe (1993), a pioneer in this research area, defined TOD as “mixed-use community within an average 2000-foot walking distance of a transit stop and core commercial area”. He found that TOD needs high-density areas with various residential, commercial, administrative, and recreational land uses. Additionally, these areas should provide an appropriate walkable environment and encourage people to make their trips by bicycle and public transit systems.

Adequate access to public transit services reduces traffic congestion, facilitates peoples travels, and improves urban quality of life (Wei et al., 2017; Zheng, Zhang, Sun, & Wang, 2017). In other words, insufficient supply of public transit results in higher levels of traffic congestion, economic loss, and environmental degradation. To improve the public transit systems, it is necessary to model, monitor, and evaluate public transport systems using effective approaches, such as the TOD planning method (Niyonsenga, 2012).

2.3. Agent-based modeling

ABM is considered a method to describe and simulate a system composed of real-world entities (Patel, Crooks, & Koizumi, 2018). In ABM, the system is composed of discrete agents or individuals interacting with each other and their environment (Shirzadi Babakan & Alimohammadi, 2016). Each agent is an identifiable unit of a computer program with autonomous and goal-directed behavior (Prudkov, 2010). The interactions among agents provide aggregated attributes, which