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Sustainable station-level planning: An integrated transport and land use design model for transit-oriented development

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ABSTRACT

Urban rail transit system in China has been rapidly constructed in response to the effects of urbanization, such as severe urban congestion and excessive air pollution. The sustainable land use planning (i.e. transit-oriented development, TOD) around the subway stations is important for the rail transit system because of its long-term influence on travel demand. However, there are limited studies that focus on the station level TOD planning. In this context, the aim of this study is to propose a multi-objective programming model that integrates transport and land use design for station-level TOD planning. In this study, one subway station in Beijing City is taken as the case, considering the unique features of urban development (e.g. high density and diversity), five objectives are taken to account in our model, including rail transit ridership, compactness, accessibility, conflict degree, and environmental effects. Meanwhile, an improved immune-genetic based algorithm is designed to obtain the optimal solutions under alternative land use schemes. The model results show that the proposed algorithm is superior to conventional genetic algorithms. This study is hoped to provide sustainable station-level planning for urban planning decision-makers.

1. Introduction

If properly designed, mass rail transit (MRT) systems can significantly enhance urban transportation service by attracting passengers from other more expensive modes of transportation and reducing their dependence on private vehicles. MRT systems have been identified as an efficient way to ease urban traffic congestion and energy consumption, reduce the environmental effects of transportation, and promote economic growth (Knowles, 1996; Bhattacharjee and Goetz, 2012; Huang et al., 2016). Numerous megacities worldwide have begun establishing MRT systems, particularly in fast-growing developing nations. In mainland China, 95 rail transit lines were in operation in 22 cities by 2014. The Beijing subway system included 18 lines and 334 stations with 554 km of MRT network by 2015 (Ma et al., 2013, 2017a, 2017b). Numerous cities have plans of expanding and upgrading their existing MRT systems, and a few cities have plans of building new systems. Notably, the performance of an MRT system in terms of coping with rapid urbanization and the increasing number of private vehicles is largely dependent on the land use layout in the serviced areas and the efficiency of relevant resource allocations (Lin and Gau, 2006). Therefore, rather than separately consider MRT systems and relevant land use, a good planning strategy should integrate both aspects into the transit-oriented development (TOD) aspect of the urban spatial structure planning (Ding et al., 2017a). TOD devises urban development plans based on public transportation systems to enhance the sustainability of MRT systems, land use efficiency, and traffic operation effectiveness.

Numerous studies have explored TOD theories and strategies for region- and station-level planning. The planning strategies of TOD generally include raising transit ridership, diversifying land use types, and increasing the use of mass transit (Bernick and Cervero, 1997). In the past decade, built environment has been considered a critical factor in TOD planning to improve MRT sustainability by combining economic and social factors (Chiou et al., 2013; Cruz and Katz-Gerro, 2016; Wey et al., 2016). Several detailed TOD planning methods have been explored according to their relevant strategies

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and principles, such as analytical mathematical models, to assist planners. The purpose of establishing analytical TOD models is to obtain alternative schemes of land use plans around subway stations, including locations, types, and area sizes. Several studies have established different TOD models for land use planning (Lin and Gau, 2006; Lin and Li, 2008). Specifically, a China TOD model was firstly established for China cities by Li et al. (2010) and was tested using the Shenzhen MRT station as a case study. However, despite these preliminary studies, the TOD model is still insufficient and requires further exploration. First, the TOD models in the current literature can be modified and extended into a station-level TOD, especially when integrating land use and transport. Second, the solution algorithm of the model can be improved to generate better results. Third, few studies have focused on the application of the TOD model for cities in China. Although the TOD model of China has been established by Li et al. (2010), the model should still be adjusted and modified for application in other Chinese cities to accommodate high population density and high land use density.

In the context of China's urbanization, this paper presents a station-level TOD planning model with five objective functions: maximizing rail transit ridership, compactness, and accessibility, and minimizing conflict degree and environmental effects. The primary contributions of this study are three-fold: (1) The multi-objective programming model integrates both land use and transportation factors, while previous studies commonly neglect the contribution of transportation for station-level planning (Ding et al., 2016). The index of accessibility in this study is used to measure the influence of transportation. (2) Taking a real station area in Beijing (the Nan Shao Station area) as an example, a case study is analyzed to identify feasible solutions for this model. The model proposed in this study extends the application of TOD in China. (3) An immune-genetic based algorithm (IGA) is improved to search for non-dominated solutions for the TOD planning model, producing a set of alternative land use schemes. The results are analyzed and compared with those of the cumulative genetic algorithm (CGA) (Xiong and Schneider, 1995; Lin and Feng, 2003) to verify the superiority of the improved IGA in this study in solving the proposed model.

The rest of the paper is organized as follows. Section 2 provides a review of the literature on TOD planning. Section 3 describes the framework of the TOD planning model. Section 4 presents the details of the TOD plan model. Furthermore, the improved IGA is briefly described in terms of the preparation for solving the multi-objective TOD planning model. In Section 6, a case study is analyzed to verify the effectiveness of the model. The conclusion is provided in the last section.

2. Literature review

TOD is generally considered a development model for enhancing the efficiency of land use and transit operations (Lin and Gau, 2006; Lin and Li, 2008). TOD is compatible with the relatively high land use density around urban subway stations. The principles and strategies of TOD planning have been studied in detail by Beimborn et al. (1991), Bernick and Cervero (1997), Andrew and Fan (2016), Lyu et al. (2016), Wey et al. (2016), and Yang et al. (2016). The basic strategies of TOD planning were classified into three aspects by Cervero and Kockelman (1997): raising transit ridership by increasing the development density of land use, improving the convenience for transport passengers by diversifying the land use types, and increasing the use of mass transit through pedestrian-oriented walkways and transfer systems (Ding et al., 2017b). Recently, several studies focusing on sustainable transportation (Aggarwal and Jain, 2016; Li et al., 2017) and MRT sustainability have been conducted with the increasing pollution problems and unreasonable land use design. The environmental carrying capacity around a subway station in a high-density development should be considered a crucial criterion in TOD planning (Wey et al., 2016). Therefore, the strategies of TOD planning require balancing the environmental, social, and economic factors to address the requirements of a sustainable MRT.

Although the strategies and principles of TOD planning have been extensively studied, further research on the mathematical models for TOD planning is required. The TOD planning model is a special case of land use design problem (LDP). According to the theory and methods of LDP, the TOD planning model is a mathematical model for obtaining alternative schemes of land use planning around the target station, including the locations, types, and area sizes of plans. Several studies have focused on the LDP and TOD planning models. For example, the LDP model was studied by Bammi et al. (1976), Ridgley and Giambelluca (1992), Dokmeci (1993), and Martínez and Henríquez (2007) mainly for simplified transportation networks. The network design problem (NDP) was discussed by Poorzahedy and Turnquist (1982), Janson and Husaini (1987), and Xiong and Schneider (1995) under a given spatial distribution of land use types. Furthermore, several studies, such as those of Feng and Lin (1999a; 1999b), Lin and Feng (2003), and Bravo et al. (2010), integrated land use and network design. Their models considered the trip distribution and assignment to analyze the travel demand based on the land use layout and transportation network (Lin and Feng, 2003). A TOD planning model with limited land use densities was developed by Lin and Gau (2006). The model had three objectives: maximizing rail transit ridership, enhancing the quality of the living environment, and maintaining social equity in the land use plan. The model included only two land use types, namely, commercial and residential, which were allocated to the plan area without considering accessibility and compactness. On the basis of the sustainability requirement of the MRT system in China, a TOD model was first established for the cities in China by Li et al. (2010).

Modeling the TOD planning is generally a complicated problem with the following features: multi-objectives, nonlinear, and the complexity of integer programming. Genetic Algorithm (GA) (Holland, 1975) is a heuristic algorithm, and has been proved as an effective approach in dealing with large-scale problems, such as multi-objective programming models (Ishibuchi and Murata, 1998; Garg et al., 2016; Vijayaraghavan et al., 2016). Numerous studies have been conducted on the application of GA for LDP, NDP, and TOD models (Xiong and Schneider, 1995; Feng and Lin, 1999a; Lin and Feng, 2003; Li et al., 2010). To take advantage of traditional GA in tackling large-scale problems, an improved GA is designed to solve the multi-objective model in this paper. In summary, the detailed TOD planning method is a two-stage procedure: Establishing a mathematical model, and generating feasible solutions. Research on quantitative models for TOD planning is still insufficient and should be enhanced for the sustainable development of the MRT system in China, despite the numerous studies on the principles and strategies of TOD planning in a qualitative fashion. Previous studies selected different aspects to establish the land use or TOD model. We found that very scarce studies integrate transportation network modeling with the station-level TOD model. Li et al. (2010) established a station-level China TOD model; however, several key factors to measure transportation networks, such as the accessibility around the station, was ignored in their multi-objective model. Accessibility refers to the convenience of reaching one location from another (Levinson and Krizek, 2005) and is an important factor in studying the inter-relationship between land use and transport (Wegener, 2004). People tend to live and work in highly accessible regions. Therefore, due to the high-density population and the limited urban space resource in the megacities of