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Exploring the polycentric city with multi-worker households: An agent-based microeconomic model

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ABSTRACT

We propose an agent-based dynamics which leads an urban system to the standard equilibrium of the Alonso, Muth, Mills (AMM) framework. Starting for instance from a random initialization, agents move and bid for land, performing a kind of local search and finally leading the system to equilibrium rent, density and land use. Agreement with continuous analytical results is limited only by the discreteness of simulations. We then study polycentrism in cities with this tool. Two job centers are introduced, and the economic, social and environmental outcomes of various polycentric spatial structures are presented. We also introduce two-worker households whose partners may work in different job centers. When various two-worker households are mixed, polycentrism is desirable, as long as the centers are not too distant from each other. The environmental outcome is also positive, but housing surfaces increase.

1. Introduction

The Earth's population is now predominantly urban, and urban areas are rapidly expanding (Seto, Fragkias, Güneralp, & Reilly, 2011). In addition to social and economic issues, this process raises environmental concerns regarding biodiversity conservation, loss of carbon sinks and energy use. Empirical evidence shows that various urban development patterns significantly influence carbon dioxide emissions (Glaeser & Kahn, 2010). Low density results in increased vehicle usage, while both low density and increased vehicle usage lead to increased fuel consumption (Brownstone & Golob, 2009). Compact urban development would be the natural answer to these issues, but the debate regarding welfare, distributive and environmental aspects is fierce between the opponents and promoters of compact cities (see e.g. Gordon & Richardson, 1997; Ewing, 1997). The issue of spatial and social structure and operation of cities has never been so acute, and there is an obvious need to better understand city spatial development (Anas, Arnott, & Small, 1998).

We present an agent-based simulation model, which answers the need to overcome the issue of analytical tractability and to consider spatial dynamics and heterogeneity, while being explicitly based on microeconomic behavior of agents (Irwin, 2010). This model is grounded in the classic urban bid-rent framework (hereafter referred to as the AMM model): Alonzo's (1964) monocentric model of land market, Muth's (1969) introduction of housing industry and Mills' (1967; 1972) model. This analytical framework has proved its robustness in describing the higher densities, land and housing rents in city centers (Spivey, 2008; Mills, 2000), despite its limitations – among others, the monocentric assumption.

Polycentrism (that is the clustering of economic activities in subcenters along with the main center) is indeed a reality, as shown by empirical evidence (for instance Giuliano & Small, 1991). However, introducing polycentrism in the AMM model proves difficult from the point of view of analytical tractability. Wheaton (2004)

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challenges monocentrism, based on empirical evidence from US cities, which shows that employment is almost as dispersed as residences. However, in this work, simplifying hypotheses are needed for analytical tractability, such as an exogenous density (consumption of land per worker is fixed and independent of location). In other approaches, centers (and sometimes subcenters) are given exogenously (Hartwick & Hartwick, 1974; White, 1976, 1988; Sullivan, 1986; Wieand, 1987; Yinger, 1992). In Fujita and Ogawa (1982), no centers are specified a priori and multiple equilibria are shown (monocentric, multicentric or dispersed patterns). Here again, since the model is not analytically tractable, simplifying hypotheses are required (e.g. lot size is fixed). Lucas and Rossi-Hansberg (2002) go further into endogenous polycentrism. A well-shared conclusion of these papers is that numerical simulations are needed.

Regarding income heterogeneity of residents, Straszheim (1987) points out that with multiple classes of bidders, it is difficult to find realistic specifications of income distribution functions which yield tractable results and, again, this requires numerical solutions. Fujita (1989) describes a principle of numerical resolution when the population is divided into several income groups.

Different agent-based models are used in urban economics to study complex models with heterogenous agents and space, and sometimes applied to real data. Benenson (1998) introduces an (economic) agent-based model of population dynamics in a city but without bid-rent mechanism. Caruso, Peeters, Cavailhes, and Rounsevell (2007) integrate urban economics with cellular automata in order to simulate peri-urbanization. Huang, Parker, Sun, and Filatova (2013) use a similar model, with constant density, no relocation and complete market information, to simulate the effects of agent heterogeneity in interaction with the land market. The way land price formation is modeled is crucial as pointed by Chen, Irwin, and Jayaprakash (2011). Parker and Filatova (2008) design a bilateral land market, where the gains of trade are shared between buyers and sellers, which is implemented by Filatova, Parker, and van der Veen (2009). However in their model lot size is fixed. Ettema (2011) proposes an endogenous modeling of demand, supply and price setting in housing market, but his model is not yet spatially explicit regarding housing location. Huang, Parker, Filatova, and Sun (2014) propose a classification of agent-based models in urban economics, according to which our model implements agent heterogeneity, explicit land-market representation with bidding and budget constraint, and socioeconomic outcomes. Moreover, compared to previous agent-based models, our own model includes variable endogenous density, agent relocation and imperfect information.

The main methodological innovation of this work is the approach by which we find the equilibrium of urban economic models. Departing from previous agent-based systems in urban economics, we use a method inspired by local search optimization algorithms in computer science (Lenstra, 2003). Starting from a random configuration, the system is led towards the optimum with local moves. Local search algorithms can usually be defined simply in a few words, but proved very efficient in solving complex optimization problems. They are used in combinatorial optimization, and linked more generally with asynchronous dynamics in game theory or statistical physics, but we adapt the method here to the framework of urban economics. There is already some analytical and simulation work in the literature on simple urban models, close to game theory, like Schelling's spatial segregation model (see for instance Zhang, 2011; Grauwin, Goffette-Nagot, & Jensen, 2012) or related urban models with a simple description of price (Lemoy, Bertin, & Jensen, 2011). However, to our knowledge, this is the first time that such ideas are used with agent-based systems in urban economics. These ideas allow us to develop a robust method for solving urban economic problems.

Two research questions are explored in this work. The first one consists in finding what kind of simple agent-based dynamics can lead to the equilibrium of the standard urban economic model. By adapting local search methods to urban economics, we find such dynamics, and we use it to tackle our second research question: what are the socio-economic and environmental outcomes of the polycentric city?

Regarding the first research question, we use here an agent-based model to find which kind of simple dynamics could underlie the standard equilibrium urban economic model. Indeed, cities are dynamic systems, in constant evolution. Therefore, the urban economic equilibrium can be seen as the result of some dynamics. It is clear that this dynamics corresponds to a bidding process, as land goes to the highest bidder in the AMM model. Another feature is that agents move between locations to increase their utility: at equilibrium, no move can allow an agent to increase his utility. On the basis of these points, we propose a simple asynchronous dynamics inspired by local search methods, that leads the urban system from any configuration to the standard AMM equilibrium. Note that while aiming for parsimony and simplicity, we also try to keep the dynamics as realistic as possible.

To answer the second question, we introduce more complexity by adding various components, in keeping with a parsimony principle. The first component is agent heterogeneity through income groups, in order to test the agreement between agent-based and analytical results. The second component is exogenous multiple centers, illustrated by two job centers at various distances from each other, which interact through competition of agents for housing. These exogenous centers may occur "naturally" when dispersive forces such as congestion or other costs of concentration overcome agglomeration economies or may originate from a government assisting subcenter formation, such as "new towns" (Anas et al., 1998). The third component is another kind of agent heterogeneity, with two-worker households whose partners may work in different job centers.

The economic outcome of the introduction of two centers is shown to be positive, as agents' utility increases when the distance between the centers increases. However, pollution linked to commuting distances decreases first when centers are taken away from each other but then increases again. Simultaneously, the decreasing competition for land results in increasing housing surfaces and thus city size. Moreover, the existence and uniqueness of equilibria in these polycentric models are discussed and various arguments are elaborated to support these features.

The remainder of the paper is structured as follows. Section 2 describes the agent-based model implementation with the microeconomic behavior of agents. Section 3 compares the simulation results with the analytical ones of the AMM model and illustrates the dynamic feature of the model. Section 4 presents the polycentric urban forms with two-worker households and their economic, social and environmental outcomes. In addition, Section 4 of the Supplementary material discusses the existence and uniqueness of the equilibrium in these models.

2. Description of the framework

2.1. Urban economic model

The AMM model was developed to study the location choices of economic agents in an urban space, with agents competing for housing (identified with land in the simplest version of the model). Agents have a transport cost to commute for work. Their workplace is located in a central business district (CBD), which is represented by a point in the urban space. Agents usually represent single workers, but they can also be used to describe households, which can be made more complex in further versions of the model. Housing is rented by absentee landowners who rent to the highest bidder, which introduces a competition for housing between agents. They