International Congress on Environmental Modelling and Software

3rd International Congress on Environmental Modelling and Software - Burlington, Vermont, USA - July 2006

Jul 1st, 12:00 AM

Applying a Multi-Agent Model to Evaluate Effects of Development Proposals and Growth Management Policies on Suburban Sprawl

M. G. Monticino

E. Brooks

T. Cogdill

M. F. Acevedo

B. Callicott

Applying a Multi-Agent Model to Evaluate Effects of Development Proposals and Growth Management Policies on Suburban Sprawl

M. G. Monticino, E. Brooks, T. Cogdill, M. Acevedo and B. Callicott

Institute of Applied Sciences, University of North Texas, Denton, Texas, 76203-0059, U.S.A

Abstract: Suburban and exurban sprawl is a major challenge facing regions worldwide. Residential sprawl and the accompanying commercial development stress municipalities providing services such as clean water, waste management, and fire and police protection. The dynamics of expanding development is influenced by complex interactions among human stakeholders and how stakeholders respond to feedback from the consequences of development decisions. This paper presents a multi-agent model coupled with a GIS-based land-use potential model that can be used by municipal policy makers to examine development scenarios. The model represents a region within the Dallas-Fort Worth metroplex (Texas, U.S.A.) facing intense residential development. Development of the model and the scenarios analyzed were done in collaboration with staff and elected officials from the City of Denton – a municipality in the midst of rapid suburban sprawl.

Keywords: Multi-agent models, Suburban sprawl, Growth management

1. INTRODUCTION

Suburban and exurban sprawl is a major challenge facing regions worldwide. Residential sprawl and the accompanying commercial development stress municipalities providing services such as clean water, waste management, and fire and police protection. Municipal governments in growing regions often attempt balancing acts of encouraging quality development that increases the tax-base and employment opportunities while maintaining the social and natural amenities that made the regions desirable in the first place [Munroe et al., 2005]. Two common growth management strategies to address this balance are zoning restrictions and open space preserves. Implementation of zoning restrictions is rarely without debate. Landowners and developers chafe at restrictions, often viewing them as a "taking" of their property rights [Renn, 2006]. While not as adversarial, locating open space to efficiently manage growth is more complex than simply acquiring the cheapest available land [Brown 2005].

To help meet growth management challenges, effective tools are necessary to allow municipal policy makers and citizens to view the potential consequences of growth management policies [Conley and Lathrop, 2005]. It is not unusual for seemingly reasonable policies to result in unintended consequences. Such consequences arise from complex interactions between the various stakeholders and the dynamics of land-use change. Consequences may be unintended, but they are not necessarily unpredictable. Modeling tools provide valuable methods for studying development dynamics and evaluating policy alternatives. Tools should capture essential features of stakeholder interactions and development patterns. In particular, an important feature is the ability to illustrate that successive development decisions are not independent of one another. Patterns of sprawl can be profoundly influenced the location of a single residential development [Inman et al 2002].

This paper presents a multi-agent model coupled with a GIS-based *land-use potential* model to investigate land-use change [cf. Ligtenberg et al., 2001 and Loibl et al., 2003]. The model represents a region within the Dallas-Fort Worth (DFW) metroplex (Texas, USA). Construction of the model and the scenarios considered were done in collaboration with staff and elected officials from the City of Denton – a municipality in the midst of the rapid suburban sprawl of the DFW metroplex.

The model provides a tool that municipal officials can use to investigate development scenarios and convey potential consequences to concerned citizens.

2. STUDY AREA AND SCENARIOS

The study area represented by the model is located in the extraterritorial jurisdiction (ETJ) of the City of Denton. Denton is the county seat of Denton County, and lies at the northern edge of the Dallas-Fort Worth (DFW) metroplex. The north central Texas region is experiencing rapid residential and commercial growth. The DFW metroplex is forecasted to grow by almost 4 million persons by 2030, reaching a population 9.1 million [NCGOG, 2006]. Similarly, the populations of both Denton County and the City of Denton are expected to nearly double by 2030 from current populations of approximately 550,000 to over 1 million in Denton County and from 100,000 to 190,000 in the City of Denton. Land-use change dynamics associated with this growth are typical of economically thriving metropolitan areas. Growing populations of nuclear families purchase ever-larger, single-family residences, ever-farther from the metropolitan centers, requiring municipal and commercial infrastructure. The number of single-family homes increased over 26% within Denton County from 2000 to 2005.

The model scenarios examined here were developed in cooperation with staff from the City of Denton. The scenarios involve two growth management issues faced by Denton. The first relates to a challenge presented by a large, high density, mixed-use (residential and commercial) development proposed on the northeastern edge of Denton's ETJ. The city was faced with the choice of annexing an area containing the proposed development to gain oversight of development plans through municipal zoning powers over the objections of current residents of the area and the development company, or losing control of development on the city's northern boundary. Residents felt that they would face higher taxes with little perceived benefit if annexed. City officials countered that the proposed development would adversely affect development trends in the area, destroying the rural lifestyle residents believed they were protecting by resisting annexation. A capability that would have been useful to city officials in making their annexation argument is a modelling and visualization tool that could have represented potential development patterns under various scenarios. We worked with city officials to embed factors affecting such development dynamics within an existing multi-agent land-use change model. The new model will provide a useful tool for similar development issues that will inevitably occur. (The Denton City Council eventually approved the annexation, which is being fought by the developer in court [Despres**,** 2005a, 2005b]),

A second complementary scenario of interest to city officials is how open space preserves affect development dynamics. Previous work by Monticino et al. [2006] indicates that considering landowner values when formulating growth management strategies may lead to more successful outcomes. For the current application, the focus is more on illustrating how locating open-space preserves at specific sites affects development patterns.

3. MODEL OVERVIEW

The model consists of two main components – a GIS-based development potential model and a multi-agent model that represents interactions between human stakeholders affecting land-use decisions. Both components were programmed (from scratch) in C. Because of space considerations, only an outline of each component is given. More details are presented in Monticino et al. [2006].

3.1 Development Potential Model

The development potential model scores the suitability or potential for development for each parcel of undeveloped land within the study area; and, if the parcel was to be developed, the relative suitability of development categories is calculated. For each type of development – residential, commercial, and industrial – three categories are defined. For example, residential developments can be high, medium or low density. In the study region, a high-density residential development would typically be eight single-family homes per acre constructed by a national homebuilder and marketed to moderate-income homebuyers. A typical low-density residential development would be higher priced homes on at least ½ acre lots built by a local custom homebuilder and marketed to high-income buyers

Factors used to estimate the development potential of a parcel include distance to the nearest major road, distance to the nearest road (major or minor), population density within a specified radius around the parcel, density of each development category within a specified radius around the parcel, and the existence of natural impediments within or surrounding the parcel – e.g., a flood plain. The model updates each factor for each undeveloped parcel after each time step of the overall simulation. Thus, the development potential model responds to successive changes in land-use. The influence of the various factors can be adjusted to account for differing assumptions. For instance, if it is assumed that low density (high-priced) residential development is more likely to locate near high-end commercial developments than away from them, then the model can be adjusted to reflect that assumption. This allows users of the model to explore a variety of "what-if" scenarios.

The development potential model interacts with the multi-agent model in two ways. First, the development potential scores are used to derive development category probabilities for each parcel. If a parcel becomes available for development (as described below), then the development category initially assigned to that parcel is selected according to these probabilities. Second, a land price (per acre) is associated with each undeveloped parcel based on its overall development potential. Parcels with high development potential are assigned a higher land price than parcels with low potential.

3.2 Multi-Agent Model

The multi-agent portion of the model attempts to capture essential features of the decision processes and stakeholder values that influence land-use dynamics in the study area. Four classes of agents representing stakeholders are defined. Landowner agents represent owners of large undeveloped parcels of land suitable for residential, commercial or industrial development. Developer agents model residential, commercial or industrial land developers. Homeowner agents represent collections of residents within a particular tract of land. Homeowner agents are assigned a weight representing the number of residents in the tract and their influence on land-use decisions – e.g., homeowner agents representing a large number of high-income residents are assigned a higher weight than agents representing sparsely populated low-income tracts. Government agents characterize municipal governments that can approve, modify or reject development proposals.

Several types of agents are defined within each agent class. Agent types are characterized by value structures that influence the actions selected by the agent. A set of available actions is specified for each agent. Agents select the action that best conforms to their values. These values are quantified within a statistical decision analysis framework (see, for instance, [Keeney and Raiffa, 1993]). Agents evaluate the worth of each available action according to a multi-attribute utility function and then select that action with the highest expected utility. The utility functions encode the essential value attributes and tradeoffs in stakeholder decisions. For the study area, utility functions were developed from focus group sessions (including with City of Denton staff and elected officials) for the landowner, developer and government agent classes and from a formal conjoint analysis survey for the homeowner agents. Cluster analysis was then performed to identify groups of homeowners with similar values. A typical value structure was identified for each cluster and then was used to define a homeowner type. This set of homeowner types is used to populate the model. Similar, but less formal, methods were used with the focus group data to derive landowner, developer and government agent types.

3.3 Model flow

Figure 1 gives a schematic illustrating the interactions between the agents, development potential, land prices, and the natural systems model. The natural systems model provides feedback to government and homeowner agents on the effects of development on land-cover changes, hydrological metrics such as rainfall runoff, sediment yield, and nutrient concentration, and wildlife habitat quality. The flow of the overall model proceeds as follows.

- At the beginning of a time step (typically a one year increment), landowner agents decide whether to hold or to sell their land. If the decision is to sell, then the land becomes available to developer agents.
- The development potential model is used to select a development category for any land available for development
- After the development category is chosen, a developer type is selected probabilistically as a function of the current government agent type. Developer types are characterized by the development proposals they will make.
- Developers submit development proposals to the government agent. Homeowner agents affected by the proposals are notified.

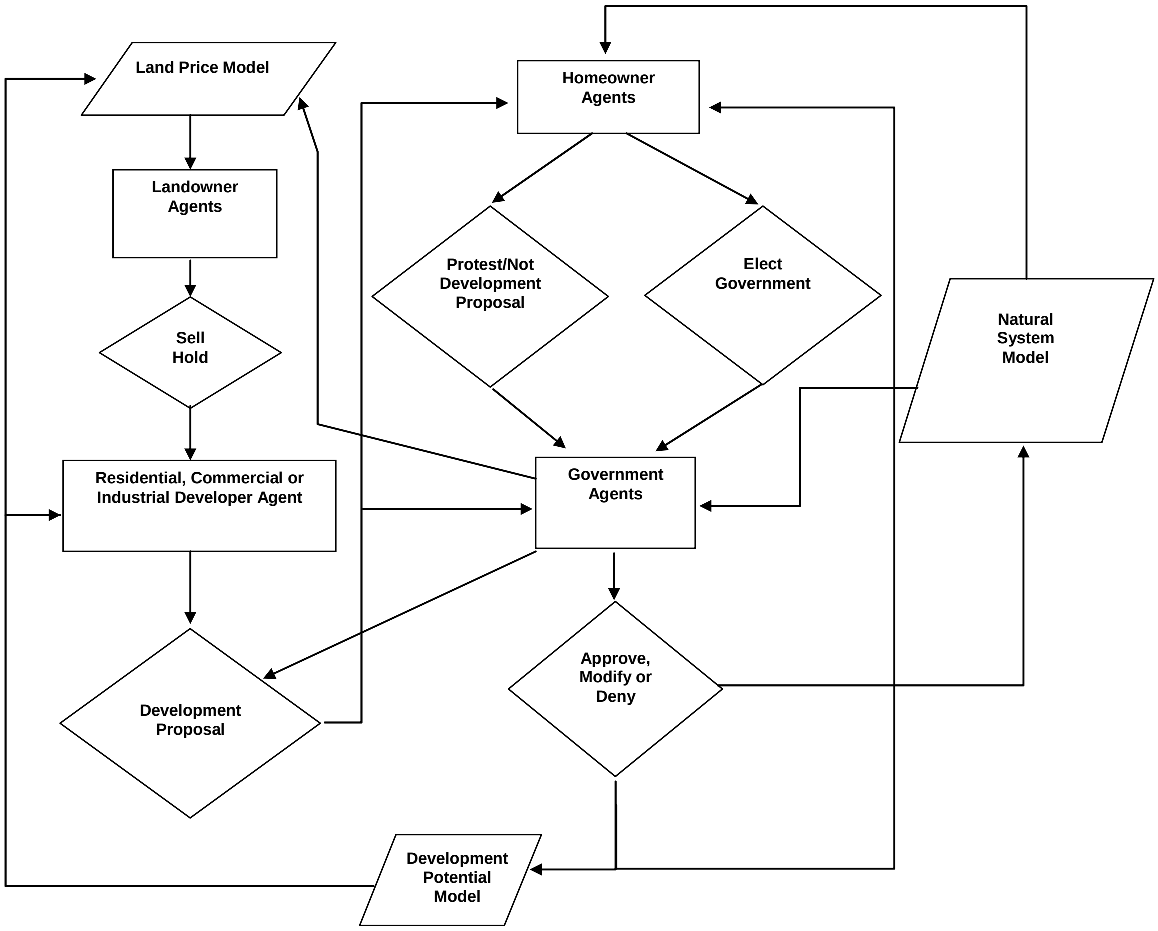

Figure 1. Schematic showing interactions between agents, development potential, land prices, and natural systems model.

- Homeowner agents then decide whether to protest the proposed development or not. The protest decision is based on the homeowner agent type, the development proposal, and the type of residential development in which the homeowner agent resides.
- Government agents decide whether to approve, approve with modifications, or reject development proposals. Decisions are based on the government agent type, development proposal, weights of the homeowner agents protesting, and feedback from the natural system model.
- Once government agent decisions are made for all pending proposals, any changes in land-use are passed to the natural system model. Parcels that have become residential developments are assigned a homeowner agent. Homeowner agent type and weight is a function of the proposal type approved.
- Before the next time increment, the homeowner and government agents receive feedback from the natural systems model. Based on this information and the government agent's decisions, homeowner agents may modify their values – i.e., change type.
- Homeowner agents vote on the government agent type that will be in power for the next time iteration. Different homeowner agent types vote for the various government agent types with different probabilities. Election results are determined by the weights of the homeowner agents casting ballots. The new government agent is in place at the start of the next time increment.
- The next iteration begins again with the current set of landowner agents deciding whether to hold or sell their land.

4. MODEL APPLICATION

To demonstrate the utility of the model, simulations were performed to study the effect of a new development or a newly established open-space preserve located at the site of the proposed development in Denton's ETJ discussed above. Four different states of land-use were considered for the test parcel – high-density residential development, low-density residential development, the parcel's current undeveloped state as a ranch, and a permanent open-space preserve. For each scenario, the model was simulated 200 times over 35-year time horizon. The category of each developed parcel in the study area was recorded at the end of each simulation. As mentioned, residential developments are categorized as either high (HD), medium (MD) or low density (LD). The proportion of developments of each category was averaged across all 200 simulations. Table 1 gives these average proportions across the entire study area, Table 2 gives the proportions in a 100 km^2 area centered at the test parcel, and Table 3 gives the proportions calculated in a 15 km^2 area centered at the test parcel.

Table 1. Proportions across study area

	Development Category of Test Parcel			
	High Density	Low Density	Open Space	Undev.
LD	59.1%	59.5%	59.6%	60.2%
MD	34.6%	35.3%	35.0%	34.6%
HD	6.3%	5.2%	5.4%	5.2%

Table 2. Proportions over 100 km^2 neighborhood

	Development Category of Test Parcel			
	High Density	Low Density	Open Space	Undev.
LD	59.6%	62.0%	61.5%	62.2%
MD	30.4%	30.8%	31.2%	30.6%
HD	10.0%	7.2%	7.3%	7.2%

Table 3. Proportions over 15 km^2 neighborhood

	Development Category of Test Parcel			
	High Density	Low Density	Open Space	Undev.
LD	55.3%	68.8%	65.4%	65.9%
MD	22.2%	23.0%	25.5%	25.0%
HD	22.5%	8.2%	9.1%	9.1%

Table 1 shows a small variation of proportions among between the four initial states of the test parcel, indicating that the parcel has an insignificant effect when viewed across the entire study area. This is not unexpected given the overall patterns of rapid development observed in the region. However, the development category of the test parcel has a pronounced local effect on development patterns. For example, Table 3 shows a significant difference in the proportion of high-density development resulting from the test parcel being a high-density development.

Figures 2 and 3 show simulated land-use change within the 100 km^2 neighborhood of the test parcel 35-years out under two scenarios. These realizations are typical of the simulations from the associated scenarios. Note the increased level of high-density development around the test parcel if it is set to high-density (Figure 2) compared to when the test parcel is initially undeveloped (Figure 3). Such visualizations can be much more effective in conveying the possible consequences of growth management policies, or lack of them, to concerned citizens than solely presenting quantitative data.

Figure 2. Simulation results at 35 years when target parcel (black) is set to high-density development. Gray shades from lightest to darkest are LD, MD and HD. White indicates undeveloped parcels.

5. CONCLUSIONS

An objective of our work was to extend a model that was originally developed as a research tool to study broad patterns of land-used change dynamics into tool that could be responsive to the needs of municipal policy makers faced with specific growth management decisions. Working with officials from the City of Denton, the resulting preliminary model combines features from multi-agent and GIS-based modelling, allowing "what-if" scenarios to be explored and communicated to citizens. The model has the inherent capability to be an effective policy tool for municipal decision makers, but it is only a first step. In particular, feedback from potential users indicates two features need to be addressed to increase its utility. First, the visualization capability should be enhanced to be more evocative when model output is viewed by stakeholders. It is easy for model developers, who are accustomed to interpreting quantitative graphics, to forget the importance of more intuitive visualizations when communicating to the general public. Current work to address this involves using digital images of development categories – e.g., photos of high-density residential developments, farmland, and forested parcels – to represent results of development simulations. Second, an important issue is the validity of the model assumptions. The development potential model includes several assumptions that drive model results. For example, the assumed magnitude of the effect of residential development types in attracting or repelling adjacent developments has a significant impact on simulated land-use dynamics. It is straightforward to modify these assumptions to investigate various scenarios. However, city planners expressed the strong need for data to guide model assumptions. A specific interest to the City of Denton is the net tax-base affect of having a series of open space preserves. In particular, what assumptions about the attractiveness of open space to high-end developers need to be made before the increased taxes collected from higher priced homes offsets the potential taxes loss by setting aside open-space. Based on the expressed importance of empirical calibration, current work involves utilizing historical remote sensing data from the north Texas region to inform the development potential model, and collecting data from communities that have implemented open-space plans to serve as analysis benchmarks.

Figure 3. Simulation results at 35 years when target parcel (black) is initially undeveloped. . Gray shades from lightest to darkest are LD, MD and HD. White indicates undeveloped parcels

6. ACKNOLEDGEMENTS

An NSF grant (CNH-BCS-0216722) provided partial support for this work. We wish to thank our colleagues in the City of Denton for their valuable contributions.

7. REFERENCES

Brown, D.G., Page, S.E., Riolo, R., Rand, W., Agent-based and analytical modeling to evaluate the effectiveness of greenbelts. *Environmental Modelling & Software* 19(12), 1097-1109, 2004.

Conley, T., Lathrop R., Modeling the Ecological Consequences of Land-Use Policies in an Urbanizing Region. *Environmental Management*; 35(3), 278-291, 2005.

Despres, C., City annexes part of desired area. Denton Record Chronicle, December 14, 2005a.

Despres, C., Craver Ranch development on hold, Denton Record Chronicle, December 21, 2005b.

Inman, K., McLeod, D.; Menkhaus, D. J., Rural Land Use and Sale Preferences in a Wyoming County, *Land Economics*; 78(1), 72-87, 2002.

Keeney, R.L., Raiffa, H., *Decisions with Multiple Objectives*, Cambridge University Press, Cambridge, 1993

Ligtenberg, A., A. K. Bregt, & R. v. Lammeren, Multi-actor-based land use modelling: spatial planning using agents, *Landscape and Urban Planning 56*, 21-33, 2001.

Loibl, W., Toetzer, T., Modeling growth and densification processes in suburban regions – simulation of landscape transition with spatial agents, *Environmental Modeling & Software, 18*, 553-563, 2003

Monticino M., Acevedo, M., Callicott, B., Cogdill, T., and Lindquist, C., Coupled Human and Natural Systems: A Multi-Agent Based Approach, *Environmental Modelling & Software*, 2006 (online publication).

Munroe D.K., Croissant C., York A.M., Land use policy and landscape fragmentation in an urbanizing region: Assessing the impact of zoning. *Applied Geography* 25, 121-141, 2005.

NCTCOG,North Central Texas 2030 Demographic Forecast, www.nctcog.org., 2006.

Renn, O., Participatory processes for designing environmental policies. *Land Use Policy*, 23(1), 34-43, 2006.Thomas, M.R., A GIS-based decision support system for brownfield redevelopment. *Landscape & Urban Planning*; 58(1), 7-23, 2002.