MULTI-AGENT MODEL OF HUMAN VALUES AND LAND-USE CHANGE

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ABSTRACT
Residential development is a driving force affecting ecosystem and land-use change worldwide. The rate and type of development is influenced by complex interactions among human stakeholders and how stakeholders respond to feedback from the environmental consequences of development decisions. Stakeholder interactions and responses are informed by the values stakeholders hold. A better understanding of the interactions between human values and natural systems can lead to more effective growth management strategies and ecosystem sustainability. This work uses a multi-agent model to investigate the effectiveness of growth management strategies based on open-space preserves. The value systems associated with the agents and the interactions among agents are based on a study of a region within the Dallas-Fort Worth metroplex (Texas, U.S.A.) facing intense residential development. Results indicate that considering landowner values when targeting open space preserves may lead to more effective growth management strategies than solely purchasing land based on opportunity or ecological factors.

KEYWORDS
Biocomplexity, multi-agent models, growth management

1. Introduction

Residential development is a driving force affecting ecosystem and land-use change worldwide. The rate and type of development is influenced by complex interactions among human stakeholders and how stakeholders respond to feedback from the environmental consequences of development decisions. Stakeholder interactions and responses are informed by the values stakeholders hold – for instance, the degree to which economic development is valued over natural ecosystem preservation has a strong influence on the rate of development. This paper presents a coupled natural-human system model and investigates growth management strategies for locating open space preserves so as to leverage land-use values to more effectively control development. Results indicate that integrating ecological and human value considerations when targeting land as open-space may lead to more effective growth management strategies than solely purchasing land based on opportunity or ecological concerns.

The human portion of the coupled system uses a multi-agent model to capture essential features of the decision processes and stakeholder values that lead to land-use changes. This work, with study sites in Texas and Venezuela, is part of a larger interdisciplinary Biocomplexity in the Environment project supported by the U.S. National Science Foundation. The focus here is on the human system and how the stakeholder values represented by the agent models affect land-use change. The model is based on a north Texas study site within the Dallas-Fort Worth metroplex region. Besides the results presented here, the work from the north Texas site has informed on-going studies in a southeast Texas site adjacent to the Big Thicket National Preserve. Results from one of the Venezuela study sites are given in [1]. Related spatial agent-based studies include [2] where the effectiveness of greenbelts in delaying development is examined and [3] which considered landscape changes in suburban areas. In [4], a general framework for integrating spatial land-use change and stakeholder agent models is presented with some hypothetical examples related to an urbanizing area of the Netherlands. A nice overview of the use of multi-agent models for examining land-use change is given in [5].

The agents represent a variety of interacting human stakeholders, including municipal governments, land developers, owners of large tracts of undeveloped land, and homeowners. The decision models used by the stakeholder agents are based on decision-analysis utility functions derived from quantitative and qualitative surveys.

The natural systems portion of the coupled model includes a land-cover transition model, a hydrological model and a wildlife habitat model. The structure of each of these components is generic enough to accommodate the various study sites in the overall project, and yet allow the level of detail necessary to accurately represent specific systems. Succession among natural vegetated land cover types is modeled with MOSAIC using parameters estimated from detailed gap-model simulations (see [6], for instance). Managed vegetated type (e.g., pasture and farmland) dynamics and transitions to developed types are controlled by the human system model. All the natural systems models provide feedback to the human system. The land-cover transition model provides land-cover maps; the hydrological model outputs metrics derived from rainfall runoff, sediment yield, and nutrient concentration; and the wildlife habitat model gives metrics related to habitat quality.

2. Model Overview

2.1 Study Area and Agent Classes

The study area represented by the model is a region of north central Texas (Denton County), U.S.A., experiencing rapid residential and commercial growth. Denton County grew from a population of 273,575 to 504,750 from 1990 to 2003. From 1995 to 2000, the percent of developed land doubled from 13% to 26.8%; and, in just the two-year period from 2000 to 2002, the number of housing units increased by over 10% (see [7]).

The focus of the modeling effort outlined here was to capture essential features of the decision processes that lead to land-use changes within the study area. An equally important objective was to develop a modeling framework flexible enough to be adapted to regions with other land-use dynamics and stakeholder interactions. The model was designed so that it would be straightforward to include other decision attributes, value systems and available actions. Thus, lessons learned from one study site could be applied to others. Indeed this has been the case. The north Texas study has provided important guidance to the model currently being developed for southeast Texas.

The north Texas model was developed based on formal focus group sessions and quantitative surveys of area residents, local developers, real estate agents, large landowners, and municipal government officials. Four main 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 (see section 3).

2.2 Decision Flow

The model is initialized by setting parameter values for the natural and human systems. The natural system parameters characterize the current land-use and cover type of each parcel of land in the study area. The human system initialization parameters involve agent type assignments to residential and undeveloped land parcels, and assigning the initial type of government agent. Once initialized, the decision/information flow between stakeholder agents and between the natural and human systems 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.
- Once land is made available for development, a development category – residential, commercial or industrial – is selected probabilistically based on a development-potential map for the region. This map gives the likelihood of a development category based on factors such as proximity to roads, proximity to other developments, and inclusion in municipal jurisdictions. Note that if development restrictions are in place, then the model accounts for this when assigning a development category.
- 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.
- 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, proposal type, weights of the homeowner agents protesting a proposal, and environmental information provided by 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 human system model receives input (e.g., rainfall-runoff and landscape fragmentation information) from the natural systems model on the effects of the approved land-use changes. Based on this information and the government agent's decisions, homeowner agents may modify their values – i.e., change type.

- Homeowner agents then vote on the government agent type that 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.

3. Agent Decision Models

3.1 Decision Analysis Overview

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 (DA) framework (see, for instance, [8]). 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 north Texas study site, utility functions were developed from focus group sessions 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. These groups motivated the homeowner agents types defined below. Similar, but less formal, methods were used with the focus group data to derive landowner, developer and government agent types.

3.2 Multi-attribute Utility Functions

Faced with making a decision, agents define a set of possible consequences, $\{c_1(A), c_2(A), \ldots c_m(A)\}$, and respective probabilities, $\{p_1(A), p_2(A), \ldots p_m(A)\}$, for each available action A. The worth of consequence $c_i(A)$ is evaluated with a utility function of the general form $U(c_i(A)) = k_1 U_1(c_i(A)) + \ldots + k_n U_n(c_i(A))$. The functions U_j represent the partial utilities of value attributes associated with the decision. The constants $k_1, k_2 \ldots k_n \geq 0$ indicate the relative value that an agent places on the respective attributes. (The partial utilities functions take values between 0 and 1, and $k_1 + k_2 + \ldots + k_n = 1$.) The expected utility of action A is $E[U, A] = \sum_{i=1}^{m} p_i U(c_i(A))$. Agents select the action with the maximum expected utility.

Each agent class and type is described below. Because of space considerations, only an outline is presented here. More details are given in [9].

3.3 Landowner Agents

Each privately owned undeveloped parcel of land is assigned a landowner agent. Landowner agents (LAs) are assigned an initial wealth and a number of years that they have owned their parcel at initialization time. Two actions are available to LAs – hold their land and maintain its current use, or sell it. Expected utility calculations are based on the possible consequences of each action with respect to three value attributes – wealth, tradition value and neighboring land-use. Wealth is the monetary return from an action – farming or ranching income if the land is held, or profits received from selling the land. Agents assess monetary return based on an economic trend model for land prices and the present value over a given time horizon for farm/ranch income. The partial utility for wealth is given by a classic decreasing marginal utility model $U_W(m) = 1 - e^{-Rm}$. The value of R characterizes the rate at which additional wealth is discounted. Each LA is assigned a value for R at initialization. Using a marginal utility model and assigning an initial wealth to each LA allows representation of landowners with different sensitivities to farming/ranching income and changes in land prices. Tradition value represents the intrinsic worth of the land to the landowner. A farm that has been in a family for several generations may have a higher tradition value than a recently purchased "hobby" ranch. Accordingly, the partial utility for tradition, U_{Tr}, is a non-decreasing function of the time that the parcel has been owned by the LA. Here U_{Tr} was taken to be a simple step function with steps at 25-year increments. This increment approximates a generation of land ownership. The neighboring land-use attribute indicates the desirability of maintaining rural land-use when bordered by development. The partial utility for neighboring land-use, U_{NL}, is a decreasing function of the percentage of developed land bordering the landowner. LAs project historical development trends to evaluate the potential value of U_{NL} if they were to continue ownership. To evaluate U_{NL} for selling, LAs look back to the state of neighboring landuse at the start of the simulation (any benchmark could be used). That is, LAs compare what their neighborhood was to what it is becoming when deciding whether to sell or not. The neighboring land-use attribute governs the interactions between landowner agents. If neighbors of an LA sell, then that LA is more likely to sell during the next simulation iteration. How strongly an LA is affected by its neighbors' decisions is determined by the relative value that the LA places upon the neighboring land-use attribute.

The overall utility function for an LA is given by $U = k_W U_W + k_{Tr} U_{Tr} + k_{NL} U_{NL}$. Attribute weights; k_W, k_{Tr} and k_{NL}, indicate the relative value a landowner places on wealth, tradition and neighboring land-use. Each LA agent is assigned a set of attribute weights. LA types are defined by their attribute weights along with their initial wealth and wealth discount rate. For example, taking $k_W = .8$, $k_{Tr} = .1$, and $k_{NL} = .1$ represents landowners primarily interested in wealth maximization, while taking $k_W = .5$, $k_{Tr} = .1$, and $k_{NL} = .4$ models landowners placing a higher value on their surroundings.

3.4 Developer Agents

If a landowner agent decides to sell, then the land is made available for development and a development category (residential, commercial or industrial) is selected based on the development-potential map. Given the development category, a developer agent type is selected. Three types of developer agents are defined for each development category – environmentally-sensitive, environmentally-moderate, and environmentally-insensitive. Developer agent types are characterized by the development type they are likely to propose. For example, environmentally-sensitive residential developer agents are most likely to propose developments that preserve a high percentage of existing tree cover and leave more open space. Metrics defining the kinds of development proposals include housing density, percent impervious surface, percent tree cover, and pollution emission. The likelihood of selecting a given developer agent type is a function of the current government agent type and the development category. For example, if a progressive government agent is in office, then an environmentally-insensitive commercial developer is less likely to obtain a parcel than if an economic-growth government agent was in office.

3.5 Homeowner Agents

Two actions are available to homeowner agents (HAs) when faced with a neighboring development proposal – to protest the development, or not. An HA's utility function involves four attributes – economic property value, residential setting, neighboring land-use, and community effort. The partial utility for economic property value evaluates the consequence of a proposed development on the agent's home value. Residential setting represents the compatibility of residential development within the HAs immediate locality. Neighboring land-use corresponds to the suitability and perceived environmental effect of development in a wider neighborhood around the agent. Community effort measures the perceived effort in taking a particular action. The overall utility function for HAs is given by $U = k_{EPV}U_{EPV} + k_{RS}U_{RS} + k_{NL}U_{NL} + k_{CE}U_{CE}$. Four types of agents are defined – apathetic, property-value, neighborhood, and environmentalist. An apathetic HA has a large value for k_{CE} and a partial utility U_{CE} that decreases rapidly as a function of perceived effort, making it unlikely that an apathetic HA will protest a development proposal. Environmentalist HAs have high values for k_{RS} and k_{NL}, and the partial utility functions U_{RS} and U_{NL} give low values to environmentally insensitive development proposals. Thus, environmentalist HAs are likely to protest most development proposals. Property value HAs have a high k_{PV} value and their partial utility function U_{PV} is sensitive to decreases in property value. Neighborhood HAs place a high weight on residential setting.

An HA may change type in response to development decisions made by the government and natural system feedback. For example, if a property-value HA protested a commercial development that was eventually approved by the government agent and localized flooding increased because of parking lot runoff, then the agent is likely to change to an environmentalist agent. After possibly changing types, HAs vote for a government agent. The probability of voting for a particular government agent type depends on the HA type. Environmentalist HAs will vote for a progressive government agent with a high probability, while property-value HAs are more likely to vote for an economic-growth government.

3.6 Government Agents

Given a pending development proposal, the government agent (GA) selects one of three actions – approve, conditionally approve at a higher environmental sensitivity level, or reject. GAs select their action based on four attributes – business relations, citizen relations, environmental consequences, and tax base effect. Their utility function is $U = k_{BR}U_{BR} + k_{CR}U_{CR} + k_{EC}U_{EC} + k_{TB}U_{TB}$. Three GA types are defined – economic growth, moderate, and progressive. Economic-growth GAs have attribute weights $k_{BR} = .4, k_{CR} = .1, k_{EC} = .1$ and $k_{TB} = .4$, while moderate and progressive GAs place more weight on community relations and environmental consequences.

The consequences of each action and their respective probabilities are evaluated with respect to the partial utility functions. For instance, the community-relations partial utility of approving an industrial development in spite of protesting HAs will be small; whereas, the business-relations partial utility approval will be high. Perceived environmental consequences of a potential action are a function of the GA type and feedback received from natural system model on environmental consequences of previous land-use decisions. Note that the land price model responds to government agent actions that tend to increase the cost of development.

4. Simulation Results

The agent model has been used to simulate land-use change dynamics for several scenarios, varying by the initial distribution of landowner, homeowner and government types, and economic model assumptions.

The model produces land-use change dynamics qualitatively similar to those observed in the study area. The main focus of the investigations reported here was to study the effectiveness of proactive growth management strategies in the context of the north Texas study site. A policy often used to preserve undeveloped land is for governmental or non-governmental organizations (e.g., The Nature Conservancy) to create open-space preserves. Typically, land is purchased based on ecological concerns or when land fortuitously becomes available. Here we considered the impact of targeting land based on landowner values with the goal of leveraging land-use values of neighboring landowners to effectively protect more land from development. Targeting strategies were compared for hypothetical distributions of landowner types over the undeveloped land within the north Texas study area for various economic scenarios. Two main LA types were assumed – LAs oriented towards acquiring wealth ($k_W = .8, k_{Tr} = .1, k_{NL} = .1$) and LAs also focused on neighboring land-use ($k_W = .5, k_{Tr} = .1, k_{NL} = .4$). For each type, a spread of initial wealth, marginal utility for wealth, and initial time of ownership were used. The rate of land price increase was varied from low to high. Simulations were over a 25-year time horizon and began with an economic-growth GA. Approximately 5% of undeveloped land was targeted for open-space and purchased at the start of the simulation. Strategies included

- Purchasing a corridor of undeveloped land. This models an existing riparian corridor of parkland in the North Texas study area.
- Randomly scattering purchases. This strategy provides development buffers across the region attempting to shield landowners likely to sell if surrounded by development.
- Wealth-oriented targeting. This plan purchases land from those wealth-oriented landowners with the highest numbers of neighboring land-use oriented neighbors. The motivation is to remove those landowners most influenced by rising land prices and to provide development buffers to landowners influenced by neighboring development.
- Neighboring land-use (NL)-oriented targeting. Purchases from those neighboring land-use oriented landowners with the highest numbers of neighboring land-use oriented neighbors. Again, the intention is to provide development buffers to NL-oriented landowners, but do this by purchasing from those also concerned with neighboring development.
- NL-oriented size-adjusted targeting. All parcels are scored by the number of NL-oriented neighbors divided by parcel size. The highest scoring parcels owned by NL-oriented landowners are purchased. The strategy was created in response to results from the other targeted plans. The size-adjusted strategy tends to buy many small parcels, while the other targeted plans buy larger but fewer parcels.

All the strategies resulted in land other than that purchased not being developed (in the absence of open-space preserves this land was developed). Strategies that purchased parcels from NL-oriented landowners were generally more effective in slowing development than purchasing from wealth-oriented LAs. The NL-oriented targeted strategy performs best for slower land price increases, while the NL-oriented size-adjusted targeting performs best for faster increases. This appears to be the result of interactions between protesting HAs, the GA type and the economic model. When land is purchased for open-space, fewer parcels of land are sold early in the simulation. This results in fewer protests by homeowners and thus the initial GA remains economic-growth type longer. So land prices are allowed to rise longer, and ultimately this leads to increased development. The effect is most pronounced for an assumed low rate of land price increases. Since the NL-oriented targeted strategy buys fewer parcels it performs better with slower land price increases. On the other hand, when land prices are increasing fast enough to spur LAs to sell from the start, the NL-oriented size-adjusted targeting strategy buys many parcels and thus provides development buffers to more LAs than the other strategies, and hence more effectively limits development.

At some point, in all scenarios, there was a cascade of relatively rapid development with a subsequent leveling off at some percentage of developed land. The magnitude of the "stable" percentage of developed land appears to be a function of the time at which the cascade occurred and the geographic distribution of the landowner types. In fact, it appears that a considerable portion of the observed variation in the stable portion of developed land depends directly on the spatial interactions of the landowner types. Figures 1a-c show development results for three simulations differing only in the initial assignments (locations) of landowner types under NL-oriented size-adjusted targeting for a slow increase in land prices. Figure 1a shows a high percentage of development (shaded black) at 25 years, Figure 1b shows an average percentage for this scenario, and Figure 1c shows a low percentage of development. (Study region just coincidentally is shaped similar to the state of Texas.)

5. Conclusions

Objectives of this work included developing a specific model for the study area as well as a general framework that captures essential features of land-use change dynamics. Simulations produced qualitative patterns of land-use change similar to those observed in the north Texas region. This helps validate the overall modeling approach as other sites are studied and more quantitative results are derived from the model. Simulation results also indicated that considering landowner values when formulating growth management strategies may lead to more successful outcomes. However, not unexpectedly, stakeholder (agent) interactions produced complex dynamics. The simulations illustrated key sensitivities of these dynamics. In particular, principal drivers of land-use change were the land-price assumptions, sensitivities of landowner agents' decisions to changes in land prices and neighboring development, and the spatial interactions between landowners. Accordingly, an important component of current work in the Big Thicket study site is a comprehensive land-use value survey of individual landowners in that region. The landowner survey pool consists of all owners of 100 acres or more of undeveloped land within the study region. The intention is to analyze land-use change dynamics with specific placement of landowner types (while respecting survey participants confidentiality).

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7. References

[1] Barros, R., Davila, J., Moreno, N., Quintero, R., Ablan, M., Modeling of the biocomplexity at Caparo Forest Reserve, in: *iEMSs 2004 International Congress: "Complexity and Integrated Resources Management"*, Pahl-Wostl, C., Schmidt, S. and Jakeman, T. (eds), Osnabrueck Germany, 2004.

[2] Brown, D.G., Page, S.E., Riolo, R., Rand, W., Agent-based and analytical modeling to evaluate the effectiveness of greenbelts. *Enviromental Modelling & Software*, in press.

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

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

[5] Parker DC, Manson SM, Jansen MA, Hoffmann, MJ, Deadman PJ., Multi-Stakeholder Systems for the Simulation of Land-Use and Land-Cover Change: A Review, *Annals of the Association of American Geographers, 93*(2), 2003, 314-337.

[6] Acevedo M.F., Pamarti, S, Ablan, M., Urban D.L., Mikler, A., Modeling forest landscapes: parameter estimation from gap models over heterogeneous terrain, *Simulation 77*, 2001, 53-68.

[7] NCTCOG 2003, North Central Texas Council of Governments Demographic Estimates, www.dfwinfo.com

[8] Keeney, R.L., Raiffa, H., *Decisions with Multiple Objectives* (Cambridge University Press, Cambridge, 1993).

[9] Monticino M.G., Miguel Acevedo, Baird Callicot, Travis Cogdill, and Christopher Lindquist, Coupled Human and Natural Systems: A Multi-Agent Based Approach, in: *Complexity and Integrated Resources Management, Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society*, Pahl-Wostl, C., Schmidt, S., Rizzoli, A.E. and Jakeman, A.J. (eds), Osnabrueck, Germany, 2004.

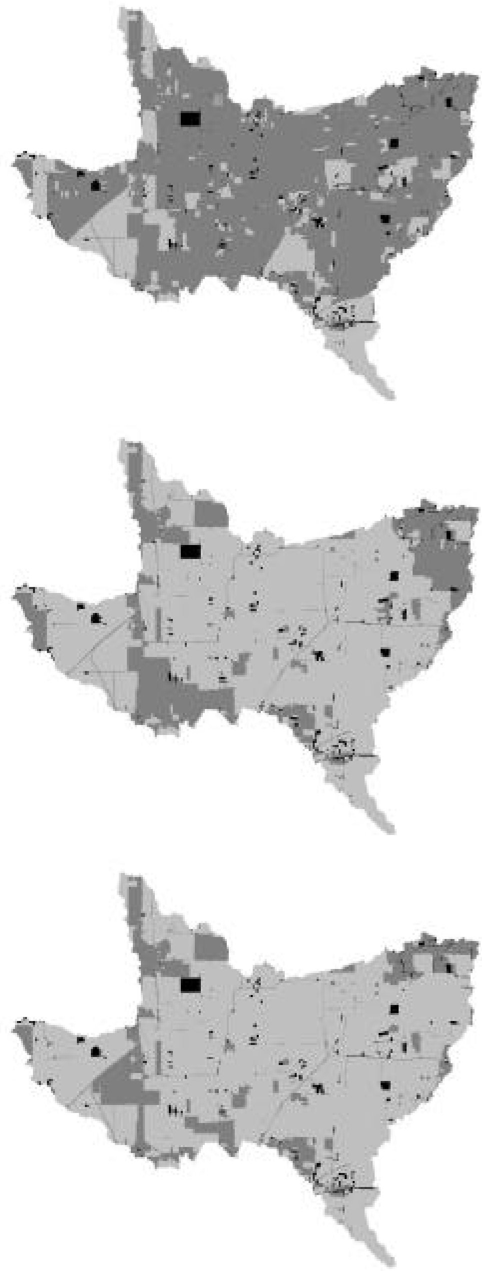

Figure 1a (top), 1b (middle), 1c (bottom). Simulation results at 25 years under NL-oriented size-adjusted targeting. Black regions mark open space preserves, light-gray indicates undeveloped parcels, and dark-gray regions are developed parcels. Simulations differed only in initial assignments (locations) of landowner types.

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