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Simulation of Urban Expansion Causing Farmland Loss and Sprawl Phenomena with Cellular Automata Technology

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Abstract

A spatial simulation model for rural and urban sprawl phenomena was developed with GIS and cellular automata techniques. The model finds out built-up areas invading toward rural areas required for development of existing urban area. Probability of land use change for optimizing the development area was determined using a land suitability analysis method interfaced with GIS methods, based on several criteria in terms of geographic and accessibility factors such as slope of land and distance from city center. Weighting values of the criteria were quantified by an analytic hierarchy process method. For model applicability test, the parameters of criteria were calibrated based on the changes in time series land use data of the test city for 1986, 1996, and 2000, which were classified by remote sensing techniques. Simulated and observed areas in land use maps for city shape of 1996 showed good similarities with each other through a morphology verification method. The model enabled us to evaluate the spatial expansion phenomena of cities considering boundary conditions, and also to simulate land use planning for rural areas in urban fringe.

Keywords : Land-use planning, GIS, Cellular automata, urban sprawl

I. Introduction

The wellbeing of human beings depends on how well they use, manage, and maintain the various living and non-living elements in the complex of ecosystems that get the Earth to have a habitable environment. Population growth in cities, modernized lifestyle and urban expansion toward rural areas have made land-use change in urban fringe areas, which is converted from forest and farmland to urbanized area such as residential, commercial, and industrial areas, including road infrastructure. Human beings' behavior has led the urbanization both in urban and rural areas, and this trend will continue in the future. After the city is saturated with the urbanized built-up areas, their demand areas should be developed outside the boundary. The urban fringe and rural areas have an open boundary and different systems from those of the inner city. Some phenomena of urban expansion toward rural

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areas, a suburbanization process, may be described by an analogy with a food chain in which predators invade victims in ecosystems. This suburbanization process has often led to urban and rural sprawl phenomena because the development was sometimes done partially in each region without global land-use planning considering the urban itself, urban fringe, and rural areas simultaneously. The sprawl phenomena have generated starfish types of city areas with irregular geometric shapes, low efficient land use, and unsustainable regional infrastructure, containing a high cost settlement system for the people. Therefore, in order to create regional land-use planning for smart even development, land-use change, urban sprawl, by human activities can first be predicted in a global region with cities and rural areas.

Many studies have been focused on land use and transportation models because land-use change has a close relationship with transportation. Development of road networks provides better accessibility to urban and rural areas; the better accessibility makes new demands of land use for urbanized areas; and the new demand generates more accessibility, so that the land use and transportation relationship can be analyzed as concepts of circulation and interaction. Accessibility factors might be considered as main factors to analyze land-use change and urbanization in urban fringe and rural areas. In this process, the urbanized area by accessibility change due to human activities should be able to be modeled and predicted spatially to make sustainable land-use planning, considering constraints such as greenbelt and zoning systems to protect urbanization.

This study tried to simulate spatially the urban expansion with sprawl phenomena using cellular automata (CA) and geographic information system (GIS) techniques, considering various criteria in terms of accessibility factors.

Ⅱ. Research method and study area

1. Theoretical framework

가. Basic theory

In an ecosystem, most people have an idea of the predation and parasitism areas between species. One species gets its nourishment from another. Although the definition of competition is not as straightforward, a wide definition can be used in this study. If two species are competing, an increase in either one harms the other, as shown in Fig. 1, in which one species replaces the other in territory. The basic theory of competition was worked out by Volterra, the mathematician, before any of the experiments were carried out.[3),4)] The present study found out some analogy between the competition concept of ecosystems and the land-use change phenomena, which were tried to simulate the urban expansion in this study. The territory change can be simulated computationally by using the cellular automata (CA) method.

나. CA model

① Governing equation of land use change by CA

Cellular space is mainly expressed as a rectangular shape, with the same concept as the grid or raster of GIS. Local states are defined as the number of cells. Neighborhood cell determined according to distance and direction from local

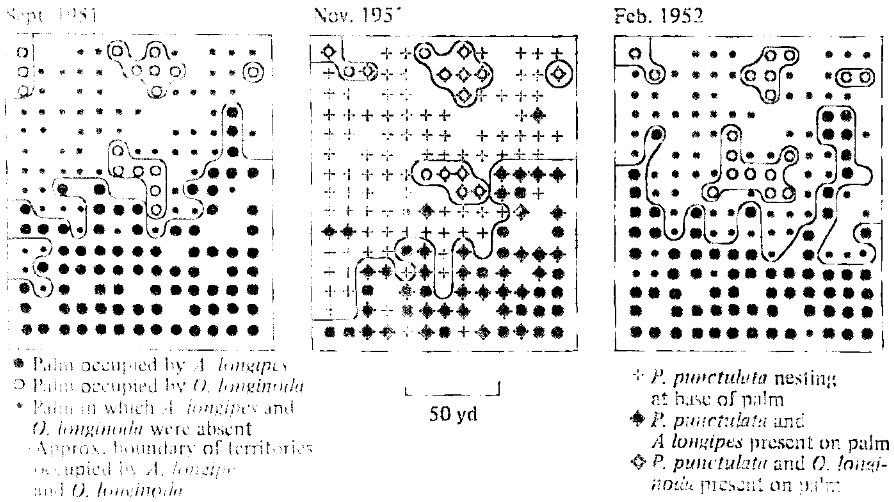


Fig. 1 A case of competition between species of plants, Anoplolepis and Oecophylla.

cells can be decided by a roving window, which is a filtering window used in grid-based GIS. Transition rule determines a process that land use type at the present time can be changed to another type the next time. A general principle of simulation by CA is to predict the future type of land use, based on the following equation (1).

$$L_i^{t+1} = f(P_{i,uv}^t, \mathbf{T}^t) \quad \cdots\cdots (1)$$

where i denotes the position of grid, t time, L state of land use, u and v states of land use that equal to L at time t and t+1, respectively, P the probability, at which the grid i will be changed from land use u at time t to v at time t+1, T a matrix of transition rule covering from time t to t+1. In the equation (1), it is critical to determine the transition rule T and the probability P.

② Transition rule

The conversion matrix for transition rule T cannot be easily determined. There are, however, several simple examples on the application of the conversion matrix. In order to consider various land use changes, this study used a general transition rule in T states (Table 1). In here Table 1 should satisfy a condition of equation (2) by a general chain rule. The future land use types can be generally predicted through the comparison of the accumulating probability and random number.

$$\sum_{m=1}^{T} P_{i,lm}^t = 1, \quad \forall l \quad \cdots\cdots (2)$$

Table 1 Transition rule in T states

Time t \ *Time t+1*		Type (1)	Type (m)	Type (T)
Land-use type	Type (1)	$P^t_{i,1l}$	$P^t_{i,1m}$	$P^t_{i,1T}$
	Type (m)	$P^t_{i,ml}$	$P^t_{i,mm}$	$P^t_{i,mT}$
	Type (T)	$P^t_{i,Tl}$	$P^t_{i,Tm}$	$P^t_{i,TT}$

③ Probability of land use change

Determination of the probability of land use change in a cell is of the most importance. Probability can be calculated based on the conditions of a present cell and its neighborhood cells. Some study only considered the probability of a present cell, ignoring the neighborhood effect.[6] Several studies gave considerations to both conditions, the former probability as an absolute probability and the latter as a relative probability.[2),7)] In order to develop the model for practical application, the present study used a new probability equation of land use change as a summation function deliberating the two probabilities and their weighting values as shown in equation (3).

$$P^t_{i,uv} = (1-w)SP^t_{i,uv} + wNP^t_{i,uv} \quad \cdots\cdots (3)$$

where w denotes the weighting value, SP the absolute probability of a present cell, and NP the relative probability of the neighborhood cells.

In equation (3), SP can be obtained through a function of land suitability value defined as equation (4).

$$SP^t_{i,uv} = f(LSS_{i,v}) \quad \cdots\cdots (4)$$

where LSS is the land suitability score and f is a function that standardizes LSS. Equation (4) assumes that no competition exists between the types of land use in a cell for development of new residential land in rural villages.

NP reflects that neighboring cells can induce the changes in the present land use type. Yeh and Li (1998) suggested equation (5) as a conditional probability for the calculation of NP.

$$NP^t_{i,uv} = \sum_{u=1}^{T} p(L^t_{i,v} \mid L^t_{q,u})B^t_{q,v} \quad \cdots\cdots (5)$$

where q denotes neighborhood cell, p conditional probability, and B is the probability of present land use among neighborhood cells. B can be determined using equation (6).

$$B^t_{q,v} = NA_{q,u} / \sum_{u=1}^{T} NA_{q,u} \quad \cdots\cdots (6)$$

where NA is the area of land use u among neighborhood cells. In the case of a 3 by 3 window, the number of neighborhood cells is eight.

④ Definition of Transition rule

Various land use types existing in the surrounding area of rural villages are requested not only to be used the land use change simulation, but also to be considered for land use planning. For the development of a simulation model, this study was classified into five types of land use based on the characteristics of rural village, i.e., paddy

Table 2 Transition rule and land conversion matrix in 5 states

Time t \ *Time t+1*		Land-use type				
		Paddy field	Dry field	Built-up area	Others	Restricted area
Land-use type	Paddy field (1)	$1-P^t_{i,13}$	0	$P^t_{i,13}$	0	0
	Dry field (2)	0	$1-P^t_{i,23}$	$P^t_{i,23}$	0	0
	Built-up area (3)	0	0	1	0	0
	Others (4)	0	0	$P^t_{i,43}$	$1-P^t_{i,43}$	0
	Restricted area (5)	0	0	0	0	1

field, dry field, built-up area, restricted area, and the others. The restricted area can also be used for comprehensive environmental control as an input condition of the model. Paddy field, dry field, and the others can be transformed into built-up area as a new residential area, according to the probability of change based on the land use suitability value, while both the restricted and the built-up areas cannot be converted into other types (Table 2).

⑤ Computational model

Although several studies have been attempted pertaining to the development of such model, the practical development and application of this model have almost not been realized up to now. This study tried to use a spatial simulation model, LUPM developed for rural villages by Kim and Chung (2002), with specific computational algorithms to overcome those problems. The model based on grid data can be initiated by receiving input data of the six criteria and the initial land use map data of ASCII format converted using GIS tools such as ARC/INFO. It then calculates iteratively the land-use change probability in all cells until the demand area will be fulfilled after receiving parameters, weighting values of criteria and demand area for new residential development. The land use change in a cell is decided through the comparison of the accumulative probability of a row in Table 1, the transition rule, and the normal random number.

2. Research methods

This study made a research procedure of Fig. 2 to simulate urban expansion spatially. The input data consist first of a potential map from several

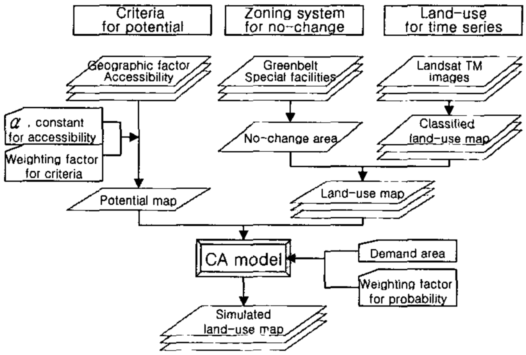


Fig. 2 Research flow diagram.

criteria maps in terms of accessibility by multiplying their weighting values optimized by an AHP (analytic hierarchical process) method. Secondly, the model needs to take the land-use maps for several data years, which can be classified from satellite images, Landsat TM. Finally, it also considers the zoning system map, which controls the no-change area such as greenbelt, agricultural promotion area, and water area.

3. Study area and data

가. Study area

The study area is Suwon city, which is located to the south of Seoul within Kyunggi Province, Korea. The study area has grown its population since 1980s, by improvement of transportation from Seoul and its surrounding areas, so that this study used the land-use and several input data of 1986, 1996, and 2000, which is the most rapid growth period.

나. Data description by remote sensing

The importance of mapping land-use classes and monitoring their changes over time has been widely recognized in the scientific community.

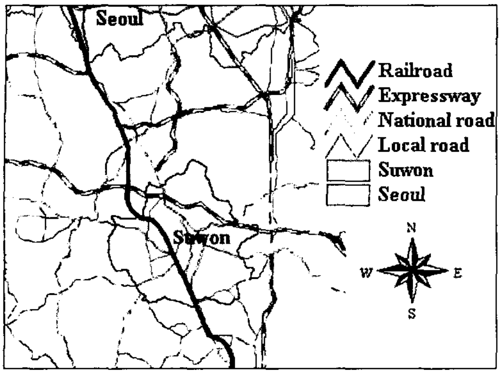
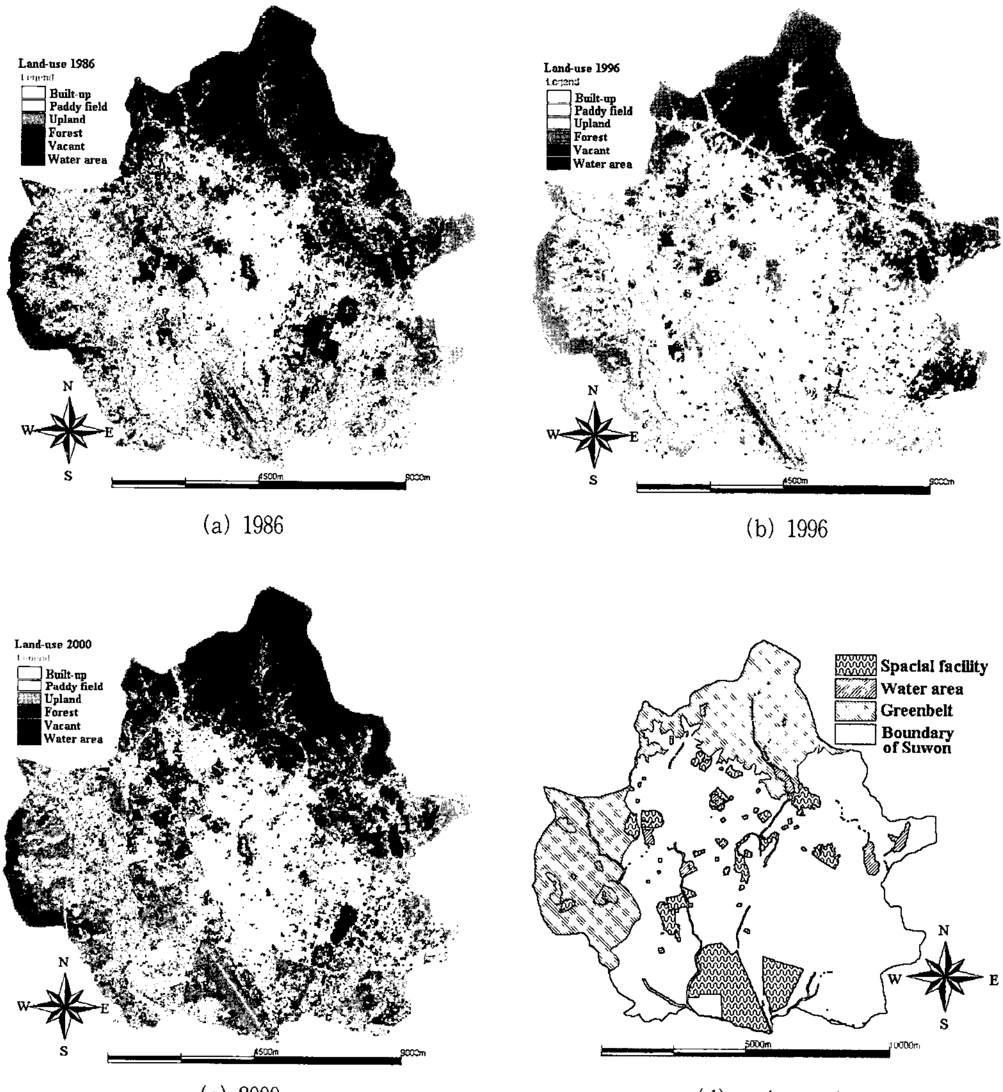


Fig. 3 Location of study area, Suwon city.

Remote sensing technique can be a time saving and cost-effective tool for providing various spatial and temporal land use data. For the analysis of spatial characteristics of serious urbanization from the 1980s to the 2000s, this study used three Landsat-5 TM images from path 116 and row 34 covering the study area. The scene dates were of April 15, 1986, April 10, 1996, and May 7, 2000. These images can be used to detect the most radical land-use change in the study area because of suburbanization process due to and its population growth and out-migration from Seoul. The quality of the images was good to excellent with no cloud cover over the study area.

Geometric correction is to remove the systematic and nonsystematic errors such as scan skew and variations in flying heights. The method of image to map rectification for the geometric correction is followed by attribute interpolation by a resampling method such as a cubic convolution resampling procedure for a mathematical transformation of the coordinates of image pixels. And then several transformation methods, such as the Tasseled Cap for brightness, greenness and wetness, indices for water, clay, iron and ferrous, and principal component analysis (PCA) for bands with information which is directly related to change, can be generated new bands to make strong differences between pixels. The new bands from these transformation methods can be effectively used to classify the land-use types. The unsupervised classification is to analyze by a cluster analysis method to produce natural clusters of pixels of similar brightness values from the multi-spectral image data without the need to train the algorithm. These clusters are then related to actual land-use/cover categories after consulting the ground truth data. The supervised classification is characterized by the need to use training areas. This approach requires knowledge of ground truth on land use/cover that can be obtained from field work or from large-scale aerial photographs.

Displacement errors of less than half of a pixel, which RMSE is less than 0.5 for all images, were recorded for the corrected images. A cubic convolution resampling procedure was used to register the images. In order to increase the classification accuracy, this study constructed 10 new composite bands, including brightness, greenness, and moisture from Tasseled Cap transformations, water, clay, iron, and ferrous from Indices transformations, and PCA 1, 2, and 3 bands from PCA. A supervised maximum likelihood classification of the study area was carried out separately for the two images, using 30 classes previously classified by an unsupervised classification method. The classified images have accuracy more than 86% and Kappa coefficient more than 0.81 for all images.



(a) 1986

(b) 1996

(c) 2000

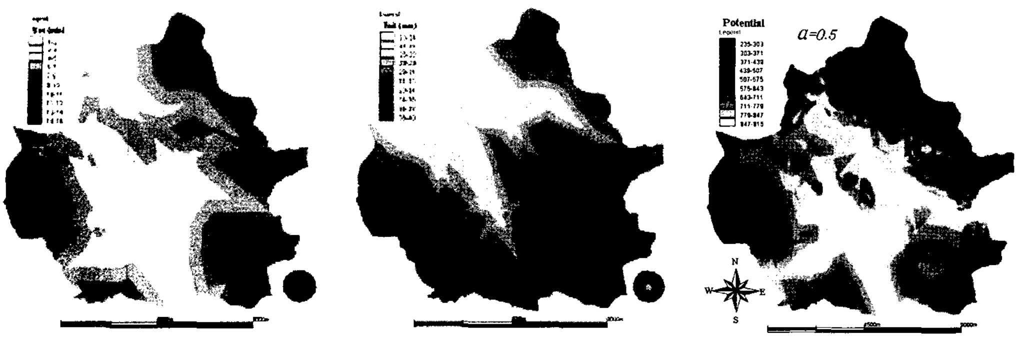
(d) zoning system

Fig. 4 Land-use maps classified by Landsat TM and a zoning system map.

Ⅲ. Results and discussion

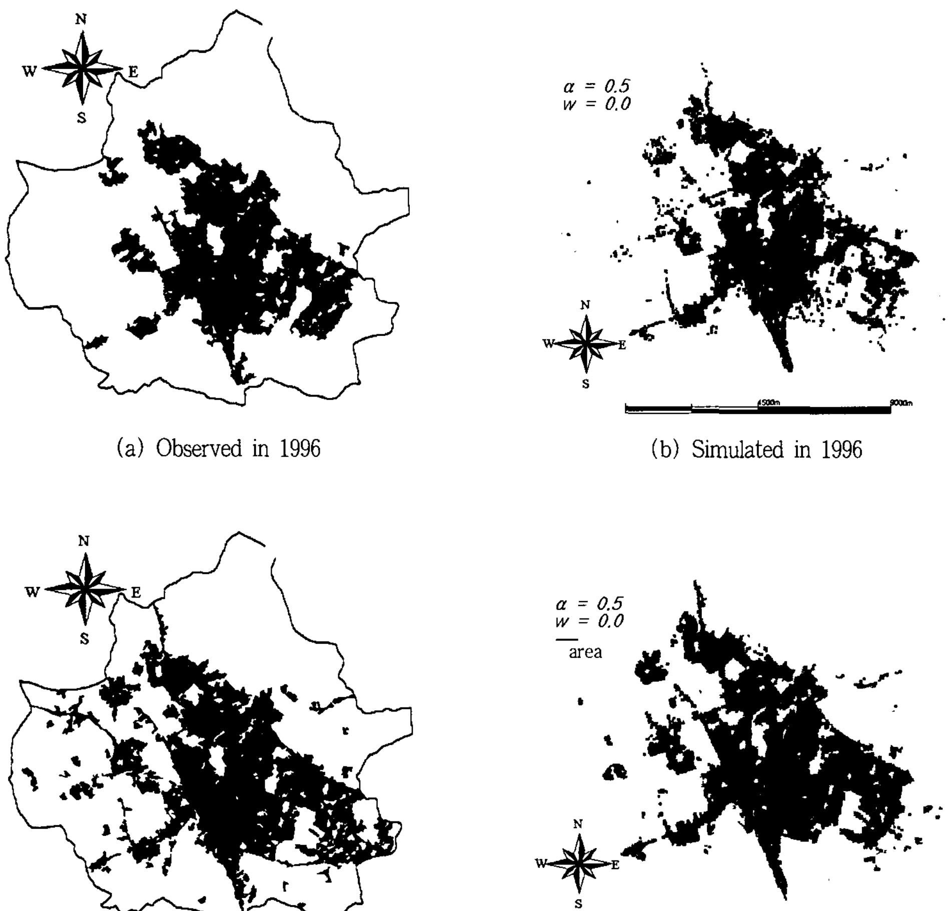
1. Model calibration and verification

The model calibration is to optimize the parameters , weighting values of criteria. This study optimized the weighting values of criteria by WSM (weighted scenario method for intensity order) in order to determine the probability whether or not the cell is changed to urban area. The criteria consist of seven factors such as one geographic factor (slope of land), and six accessibility factors (time distances from city center, national road, Seoul, station, and built-up boundary), as examples shown in Fig. 5. The optimization result determine the order of



(a) Time distance from city center (b) Time distance from center of Seoul (c) Potential map

Fig. 5 Two example maps among 7 criteria and optimized potential map.



(a) Observed in 1996 (b) Simulated in 1996

(c) Observed in 2000 (d) Simulated in 2000

Fig. 6 Observed and Simulated Built-up area maps.

weighting values, so that the AHP method calculate the weighting values by the order from the AHP intensity matrix generated in this study.

2. Application results

By the results of model calibration and verification, the optimized weighting values were applied to simulation of urban expansion from 1986 to 1996 and from 1996 to 2000. The simulation results in Fig. 6 show that the model has high accuracy in the expansion pattern of the urban area. The accuracy assessment shows that the results have high accuracy reasonably, which the relative errors of the simulated area to the observed total built-up area are 85% and 89% for the first change from 1986 to 1996 and the second from 1996 to 2000, respectively.

3. Discussion

This study has new findings that several parameters of the distributed system model with grid based CA simulation considering properties of all cells in GIS maps can be optimized by introducing the WSM method combined the ranking and AHP methods. The existing study could not show the practical application of model for the spatial expansion simulation with CA technique. The new findings show that the CA model may be used to simulate temporal and spatial expansion phenomena of buit-up area by human beings' activities in urban and rural areas. The GIS data developed in this study can be applied to advance research for urban expansion simulation because the new procedure for data processing is definite. Besides, estimating the new urban area that invades into rural area and decrease farmland and forest areas can be prime data for regional and rural planning. It also enable us to make land-use planning reasonably in urban fringe and rural areas.

Ⅳ. Conclusion

The present study tried to simulate urban expansion spatially using a CA model with three kinds of input data such as a potential map for built-up area, a zoning system map for no-change area, and land-use maps of 1986, 1996, and 2000 from satellite images of Landsat TM. The new findings of this study show that the spatial estimation of new urban area and sprawl phenomena in urban fringe and rural areas can make high potential area and new development area over time in the future. In rural area, planners may make the land-use planning with the high potential area for new built-up, so that they can have sustainable regional and rural planning for conservation of arable land and environmental areas.

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