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The California Urban Futures Model: a new generation of metropolitan simulation models

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Abstract. The California Urban Futures model is the first in a new generation of metropolitan simulation models which replicate realistic urban growth patterns and the impacts of development policy at various levels of government. It projects population from the 'bottom-up', it allocates growth to sites based on development profitability, it realistically embodies the role of accessibility in the development process, and it is operated through the medium of geographic information systems. This paper is an explanation of the rationale of the model and the way it has been built in terms of its formal structure, its databases, its decision rules which reflect the development process, and its application to the San Francisco Bay Area where it has been used to evaluate the impact of a diverse set of development policies. The paper concludes with an agenda for further model development.

1 Introduction

This paper is a summary of the theory and development of the California Urban Futures (CUF) model[1], the prototype for a new generation of metropolitan forecasting and simulation models. Its purpose is to provide a framework for simulating how realistic growth and development policies, applied at various levels of government, might alter the location, pattern, and intensity of urban development in the fourteen-county Northern California Bay Region (see figure 1)[2].

The CUF model breaks new ground in several areas. First, in contrast to most other metropolitan forecasting models (which project population growth at the regional level and then allocate it downward), the CUF model projects population growth at the city or subarea level, and then aggregates upward. Second, instead of allocating projected growth to zones (as do most other metropolitan forecasting models), the CUF model allocates growth to individual sites according to each site's potential profitability if developed. Thus, it explicitly recognizes the importance of land developers and homebuilders as central actors in determining metropolitan development patterns.

Third, following in the tradition of the Lowry model (Goldner, 1971), most urban simulation models rely on relative transportation accessibility as the primary determinant of urban development patterns (Batty, 1976; Putman, 1977; Wilson, 1974). The CUF model, by contrast, incorporates spatial accessibility (measured several different ways) as one of *many* variables that determine the location and density of new development. Fourth, it is also the first metropolitan simulation model to take advantage of the analytical power of geographic information systems (GIS) to assemble, organize, manage, and display the millions of available pieces of information describing land development potential.

[1] Earlier versions of the CUF model were known as BASS II (Bay Area Simulation System).

[2] Alameda, Contra Costa, Marin, Napa, Sacramento, San Francisco, San Joaquin, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma, Stanislaus, and Yolo.

Fifth, the CUF model can explicitly incorporate realistic development policies (pursued at various levels of government) into the growth forecasting process. Sixth, it is both easy to use and visual: new policy scenarios can be simulated in a matter of hours, and the results of those simulations can be presented in map form at almost any level of detail.

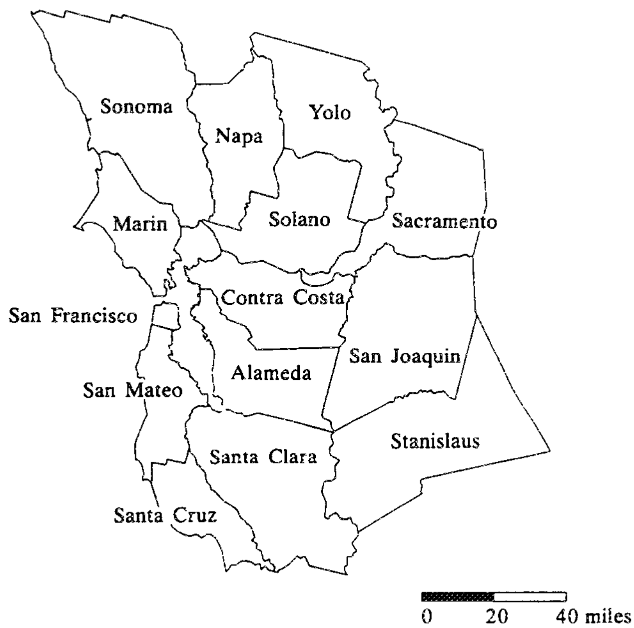

Figure 1. Fourteen-county Northern California Bay Region.

The remainder of this paper is organized into nine parts: in part 2 I summarize the four design principles that guided the development of the CUF model; in part 3 I schematically present its overall structure; part 4 is a presentation of the regression equations which form the core of the 'bottom-up' population growth submodel; part 5 is an explanation of the organization of the spatial database, the GIS part of the CUF model; in parts 6 and 7 I introduce the structure of the decision rules used to allocate projected population growth to specific areas and to annex newly developed areas to existing cities; in part 8 I explain the several ways in which the CUF model can be used to simulate development policy changes; part 9 offers an agenda for additional model development; and in part 10 I reiterate some of the unique features of the model.

2 Design principles of the model

Development of the CUF model was guided by four design principles.

2.1 A spatial simulation system, not a regional forecasting model

First and foremost, the CUF model had to be able to simulate the spatial growth of the metropolitan area as it actually occurs—site by site, parcel by parcel, block by block, and city by city. County-level and zonal growth totals, such as those produced by most current regional forecasting models, were judged to be too aggregate to provide a clear picture of the spatial processes of urban growth. Being able to simulate the specific locations *where* growth might occur is as important as being able to project how *much* growth might occur.

Our insistence that the CUF model be spatially accurate magnified both the complexity of the model, and the volume of data required to build it. This, in turn, required the use of a GIS to manage and access spatial data.

2.2 A policy-relevant approach

As the term *simulation* suggests, the CUF model is designed to simulate alternative regional development futures as a function of specific policy changes, rather than to produce a single best-guess forecast. The model must therefore be usable and reliable over a wide range of realistic policy proposals, which might be regulatory (for example, significant down-zoning of undeveloped areas) or investment oriented (for example, construction of specific new transportation facilities or wastewater facilities). Moreover, it had to be able to simulate the impacts of policies undertaken by various governmental units including state government, local government, special districts, and (potentially) regional government. The CUF model also had to be able to simulate a complex of policy proposals; that is, to simultaneously incorporate different policy initiatives as adopted in different jurisdictions.

The requirement of policy relevance mandates that political jurisdictions—cities and counties—be one of the basic units of analysis of the CUF model. Under California law, development policies are primarily under the jurisdiction of local governments, specifically cities and counties.(3)

The use of political jurisdictions as a basic unit of analysis has both positive and negative ramifications. On the positive side, because most census and state population data (and some economic data) are reported at the jurisdictional level, the task of collecting some types of data is simplified. Complications arise, however, when one tries to simulate the generation and expansion of unincorporated population centers—places that may have a popular identity but have not been formally incorporated, and for which data are usually unavailable. Some, but by no means all, of these unincorporated centers are referred to by the Census Bureau as census-designated places (CDPs).

The requirement of policy relevance also mandates that the CUF model have a 'bottom-up' structure. Traditional urban development models generally have a 'top-down' structure: population and economic growth increments are projected for large areas (typically regions or counties) and then allocated to smaller units (typically traffic analysis zones). Under such a structure, local policy initiatives affect only the differential allocation of the growth increment, not the size or nature of the growth increment. In a bottom-up model, economic and population growth is projected for each unit of analysis, and then aggregated. Thus, in a bottom-up model, local policy initiatives affect not only the location of population and employment growth, but also their size and quality.(4)

(3) Current efforts to regionalize development planning in California notwithstanding (Landis, 1993), I expect that the development approval process will continue to remain the province of local governments.

(4) Some reconciliation between the top-down and bottom-up approaches is essential. The problem with a purely bottom-up forecasting approach is that the aggregation of growth totals for smaller units of analysis may either exceed or fall short of the regional growth total. That is, either too much or too little growth will be generated. In the current model, this reconciliation takes the form of separate bottom-up city population forecasts and top-down county population forecasts; the latter forecasts then function as control totals for the city forecasts.

2.3 A tool useable by and understandable to planners and policy analysts, not just technicians
Most regional forecasting models make sense to the analysts and technicians who develop them, but not necessarily to the policymakers and planners who try to use them (Pack, 1978). To avoid this problem, the growth-allocation mechanisms in the CUF model are designed around a series of transparent and changeable decision rules (for example, "limit development densities to four units per acre in this city") rather than mathematical algorithms. Thus, it is possible to trace how specific policy changes will affect the pattern and level of population growth locally and regionally.

2.4 An expandable system
Many regional forecasting models are constructed "all-of-a-piece" (Wegener, 1994); that is, as a series of sequential and interrelated mathematical relationships. As a result, estimation and projection errors tend to propagate throughout the model, often in ways that are difficult to follow. This limitation makes many regional models quite unstable (prone to overprediction and underprediction for certain areas), and requires that they be subsequently fine tuned by human judgment. The results of this type of compromise are model forecasts that are difficult to replicate or use in a policy context.

To sidestep this problem, the CUF model is designed in modular fashion, as a system of related but independent submodels. As improved forecasting procedures, better spatial data, or better allocation-decision rules are developed, they can be smoothly integrated into the CUF model.

A modular approach also allows the CUF model to make use of *appropriate* theory. For example, although a trend-based approach may be the most appropriate way to forecast population growth, it is certainly not the most appropriate way to allocate growth to particular areas. By separating the growth-forecasting and growth-allocating functions of the CUF model, it is possible to utilize a trend model for growth forecasting, and a decision-rule-based model for growth allocation.

3 The structure of the CUF model
The purpose of the CUF model is to predict the location, pattern, and density of population growth in the fourteen-county Northern California Bay Region through to the year 2010, as a function of alternative regulatory and investment policy initiatives. It is built on two primary units of analysis: incorporated cities (and counties), and developable land units (DLUs). Population growth, the demand side of the CUF model, is projected on the basis of city population growth trends. Development potential, the supply side of the CUF model, is calculated in terms of DLUs.

Under California law, control of development and land uses rests entirely in the hands of incorporated city and county governments. Villages, towns, municipal utility districts, regional authorities, and CDPs lack control over land uses in California. As of January 1991, there were more than 150 city and county governments in the fourteen-county study area (San Francisco is both a city and a county) having direct control over local land uses and development.

Cities also have some measure of land-use control over directly adjacent, unincorporated areas. Such areas, known as spheres of influence, are established and updated by county Local Agency Formation Commissions, or LAFCOs. Spheres of influence were originally intended as flexible urban limit lines; they were the areas into which growing cities would eventually expand, and to which cities could economically provide local public services. In recent years, the value of spheres of influence as a tool for coordinating interjurisdictional land-use policies has been greatly diminished.[5]

DLUs are the second primary unit of analysis in the CUF model. DLUs are currently undeveloped or underdeveloped areas inside and outside cities which may be developed or redeveloped. They are polygon constructs generated by the GIS component of the model and are described according to the geometric union and/or intersection of various environmental, market, and policy attributes. An example would be an undeveloped site with steep slopes, served by sewers, zoned for light industrial, and that is less than 500 m from a major freeway. In more developed areas, DLUs may approximate collections of developable parcels.

Viewed in a nutshell, the CUF model 'grows' the Northern California Bay Region by determining how much new development to allocate to each DLU during each model period as a function of population growth in each city and county; the profitability potential of each DLU (if developed); and a series of user-specified development regulations or incentives. As shown schematically in figure 2 and table 1, the structure of the CUF model incorporates four related submodels.

1. *The bottom-up population growth submodel*: the demand side of the CUF model. It generates five-year population-growth forecasts for each city and county in the study region.

2. *The spatial database*: the supply side of the CUF model. GIS based, it generates and updates the geometry, location, and attributes of each DLU. It is also the primary tool for displaying the spatial pattern of growth.

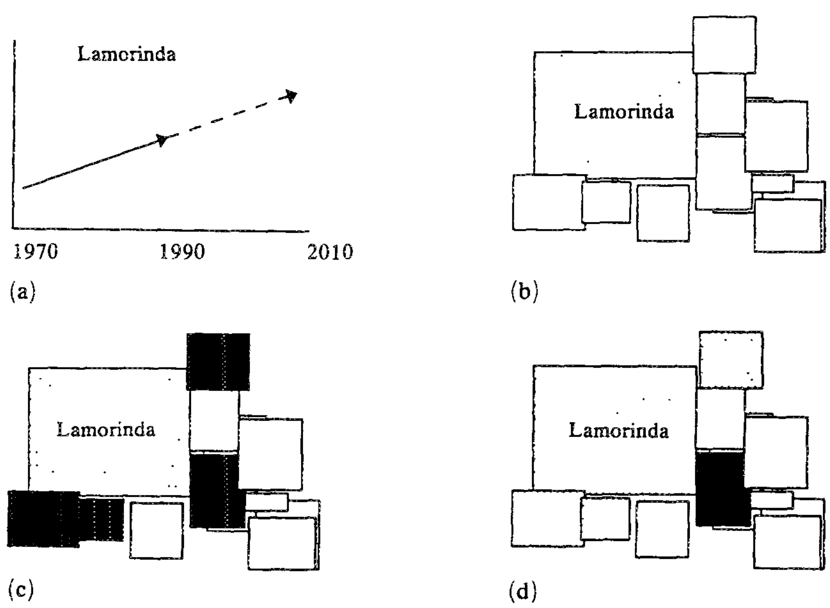

Figure 2. The logic of the California Urban Futures Model: (a) the bottom-up population growth submodel; (b) the spatial database; (c) the spatial allocation submodel; (d) the annexation-incorporation submodel.

(5) The waning of spheres of influence as a development policy tool has occurred primarily as a result of Proposition 13. Proposition 13 encourages cities and counties to engage in a practice known as 'fiscal zoning': competing with each other for developments that generate property taxes (for example, retail centers), while at the same time exporting expenditure-intensive residential development.

Table 1. Outline of the structure of the California Urban Futures Model.

Step 0. Forecast basic employment growth by county.

Step 1. Bottom-up population growth submodel
 (1) Project city population in year $t+5$.
 (2) Project county population in year $t+5$.
 (3) Calculate unincorporated population growth as a residual.

Step 2. Spatial database
 (1) Update map layers with new information.
 (2) 'Union' map layers to update list of developable land units (DLUs).

Step 3. Spatial allocation submodel
 (1) Calculate profit potential for each DLU if residentially developed.
 (2) Within each city sphere of influence, sort DLUs in order of profit potential.
 (3) Eliminate inappropriate DLUs from allocation according to local, county, regional, or state policy considerations.
 (4) Within each city sphere of influence, begin allocating population growth to DLUs in order of profit potential.
 (5) Allocate spillover growth (if any) consistent with local policies.

Step 4. Annexation-incorporation submodel
 (1) Incorporate new cities.
 (2) Annex newly developed DLUs to cities as appropriate.
 (3) Update city boundaries.

3. *The spatial allocation submodel*: a series of user-specified functions and decision rules for allocating population growth to each DLU based on potential profitability if developed.
4. *The annexation-incorporation submodel*: a series of decision rules for annexing newly developed DLUs to existing cities, or for incorporating clusters of DLUs into new cities.

The structure of each of these components is explained in greater detail in the following sections.

4 The bottom-up population growth submodel

The bottom-up population growth submodel is the demand side of the CUF model. It consists of two regression equations of population growth in the cities and counties of the Northern California Bay Region. Both equations are modified trend models. That is, they predict current population levels (the dependent variable) as a function of past population levels (CDF, various years). Other independent variables are included to account for place-specific differences from the overall trend-line.

The bottom-up population growth submodel takes its name from equation 1, shown in table 2. Equation 1 is used to project city-by-city population growth levels, at five-year increments, for 112 incorporated cities in ten counties[6]. Equation 2 is used to forecast county-wide population growth (which includes the population of incorporated cities), also at five-year increments. Projections of population growth for unincorporated county areas are estimated by subtracting the sum of city population growth (based on equation 1), from county-wide population growth (based on equation 2). Equations 1 and 2 were both estimated by ordinary least squares regression on a database which combines cross-sectional data (cities and counties) and time-series data (covering the periods 1970-75, 1975-80,

[6] Equation 1 was estimated with data from only ten of the fourteen counties in the study area: Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Santa Cruz, Solano, and Sonoma.

Table 2. Equation 1: Regression results of the ten-county bottom-up population growth submodel.

Independent variable[a]	Estimate of coefficient	t-statistic	β value
CITYPOP(t−5)	0.9367	27.03	0.89
City-size dummy variables			
VERY SMALL	(omitted to guarantee a unique solution)		
SMALL	2597.3	4.39	0.011
MEDIUM	6298.4	7.25	0.022
MEDIUM LARGE	10286.0	8.112	0.037
LARGE	15437.9	7.71	0.032
OAKLAND	51706.4	7.86	0.051
SAN FRANCISCO	162825.4	9.06	0.160
SAN JOSE	116654.7	10.69	0.114
GROWTH CONTROL(t−5)	−173.82	−2.51	−0.00054
LANDLOCK(t−5)	−234.72	−6.31	−0.021
DENSITY(t−5)	−0.00000105	−3.601	−0.116
CA-WAVE(t)	0.000000612	3.314	0.029
Constant	977.26	2.47	
R^2	0.998		
F-statistic	21496.9		
Standard error	3977.5		
N	383		

[a] The dependent variable is CITYPOP(i,t): population of city i in time period t. The independent variables are defined in the text.

1980-85, 1985-90). Coefficient estimates and relevant statistics for all three equations are discussed below.

4.1 Equation 1: city population growth trends

Table 2 presents the results of equation 1. The primary dependent variable is CITYPOP(t), the current city population; and the primary independent variable is CITYPOP(t-5), the population of the same city five years previously.(7)

Cities of different sizes tend to add new population in different increments. That is, they have different growth 'regimes' (Teitz, 1990). All else being equal, smaller cities tend to attract fewer new residents than larger ones.(8) To capture this effect, the 112 cities in the sample were classified into five size classes, according to population in year t: (1) VERY SMALL: population less than 10000; (2) SMALL: population between 10000 and 29999; (3) MEDIUM: population between 30000 and 49999; (4) MEDIUM LARGE: population between 50000 and 99999; and (5) LARGE: population greater than 100000. City-size classes were updated every five years to account for population growth. Three separate city-size classes were generated for the region's three largest cities: OAKLAND, SAN FRANCISCO, and SAN JOSE. The city-size classes were entered into the model as dummy variables.

(7) So strong is the trend effect that the R^2 measure for this single independent variable by itself is 0.994. The limitation of this model is that the standard error of the estimate is too large to be used for forecasting purposes.

(8) To identify 'city-size' classes, we developed rank-size distributions for Bay Area cities for 1970 and 1980. The points at which the slopes of the two rank-size distributions changed were used to identify the various city-size classes.

Three variables were included in the model to provide a 'brake' on population growth. The first, GROWTH CONTROL(t-5), is a dummy variable indicating whether or not the city had adopted a population, housing, or development cap. This variable is weighted by the land area of the city to account for differences in geographic size.

A second braking variable, LANDLOCK(t-5), indicates whether a city is landlocked (or water-locked) by neighboring communities, and thus prevented from expanding; this dummy variable is also weighted by the land area of the city in the previous five-year period.

The final braking variable, DENSITY(t-5), is the gross population density of the city in the previous five-year period, weighted by the population of the city in the previous period. All else being equal, we observe that cities with higher densities tend to grow more slowly than cities with lower densities.

The final variable to enter the model, CA-WAVE(t), causes local population growth to accelerate during periods of high statewide population growth. It consists of current statewide population weighted by the land area of each city in the previous five-year period.

Overall, equation 1 explains the historical trend-line of city population growth exceptionally well (R^2 = 0.998). More important from a forecasting perspective, the standard error of the estimate is extremely small. All of the coefficients are statistically significant and have the expected signs. For example, cities that are landlocked or water-locked and thus can not annex undeveloped parcels grow somewhat more slowly than cities that can expand. Cities that have adopted formal growth control ordinances also grow more slowly, as do cities with higher residential densities. And the positive sign on coefficient of the CA-WAVE variable reflects the fact that local population growth responds, albeit only slightly, to changes in statewide population growth.

The five city-size classification dummy variables capture the observed effect that population growth levels tend to be correlated with city size. For example, whereas small cities typically add about 2600 new residents every five years, large cities add about 15400 new residents every five years.

4.2 Equation 2: county population growth trends

Some of the fastest growing areas in California are unincorporated. That is, they are under the political jurisdiction of county governments. The CUF model forecasts population growth in unincorporated county areas as a residual: that is, as the difference between total county population growth and the sum of population growth within incorporated cities.

Table 3 presents regression results for equation 2, a trend model of five-year population growth during the 1970-90 period for nine of ten San Francisco Bay Region counties (San Francisco, which is also a city, is omitted). Equation 2 is similar in form to equation 1: CNTYPOP(t), the current county population, is primarily a function of CNTYPOP(t-5), the population of the same county five years previously.

Where equation 1 differs from equation 2 is in the choice of variables that explain deviations from the historical trend-line. Two variables, CHBASIC, and CA-WAVE accelerate county population growth; another two variables, GROWTH CONTROL and CITYLAND provide a brake on county population growth. CHBASIC, the numerical change in 'basic'[9] employment in the county during the previous five years, is the one variable which must be projected exogenously to the CUF model.

[9] Basic industries include industries in the manufacturing, transportation, communications and public utilities sectors, and insurance carriers.

Table 3. Equation 2: Regression results of the nine-county population growth submodel.

Independent variable	Estimate of coefficient	t-statistic	β-value
CNTYPOP(t−5)	0.67	5.34	0.62
CHBASIC	0.371	3.42	0.0175
GROWTH CONTROL	−157.75	−4.16	−0.022
CITYLND	−969.67	−7.22	−0.065
CA-WAVE(t)	0.128	3.89	0.445
R^2	0.999		
F-statistic	15368.01		
Standard error	16656		
N	56		

[a] The dependent variable is CNTYPOP(i,t): population of county i in time period t. The independent variables are defined in the text.

As table 3 indicates, CHBASIC is strongly and positively correlated with county population growth; for every job increase in basic employment in a county over a five-year period, the county's population rises by 0.37 persons. CA-WAVE is a county's share of region-wide population growth (lagged five years), and weighted by state population in the current year. It measures the extent to which statewide population growth filters down to the county level. As table 3 shows, it is both positive and significant.

In the past, persistently high rates of population growth have led many unincorporated places to incorporate in order to gain control over land-use decisions and locally generated revenues. Upon incorporating, those same places then attempt to boost revenue-generating commercial development at the expense of revenue-using population growth. All else being equal, we would expect that population growth would decline as the ratio of incorporated land area to total county land area increases. This effect is captured in the variable CITYLAND, which, as expected, is negatively correlated with county population growth.

Several counties in Northern California have adopted county-wide growth-control ordinances to slow growth, protect the natural environment, or preserve their agricultural base. Such development limits are captured in the variable GROWTH CONTROL, a dummy variable (weighted by the total land area of incorporated cities within the county) that indicates whether or not a county has adopted a population, housing, or development cap. As expected, it is negatively correlated with county population growth.

Overall, equation 2 fits the data extraordinarily well, with a goodness-of-fit measure approaching unity, and an extremely small standard error.

5 The spatial database

The spatial database consists of a series of map layers that describe the environmental, land-use, zoning, current density, and accessibility characteristics (or attributes) of all sites in the Northern California Bay Region. These various layers can be analyzed individually, or merged into a single layer which includes all the relevant attribute information for each resulting polygon. The spatial database is maintained and managed through the use of ARC/INFO, a GIS which incorporates a relational database and true map-feature topology[(10)].

[(10)] ARC/INFO (ESRI Inc., Redlands, CA) is implemented on a Sun SparcStation.

The spatial database functions as the supply side of the CUF model. It is a comprehensive list of the locations and attributes of currently undeveloped (or underdeveloped) sites that may be available to accommodate city and county forecast population growth. These sites are known as DLUs. DLUs do not have regular shapes or sizes, but are generated as the geometric union of different map features and their attributes (figure 3). Depending on how the different map layers combine, DLUs can vary in size from the very small to the very large. DLUs in or adjacent to urbanized areas tend to be very small, typically a few acres. By contrast, DLUs in rural areas may exceed several hundred acres in size. The number of DLUs varies by county, but also tends to be very large—ranging from more than 25 000 in Santa Clara County, to fewer than 10 000 in Solano County.

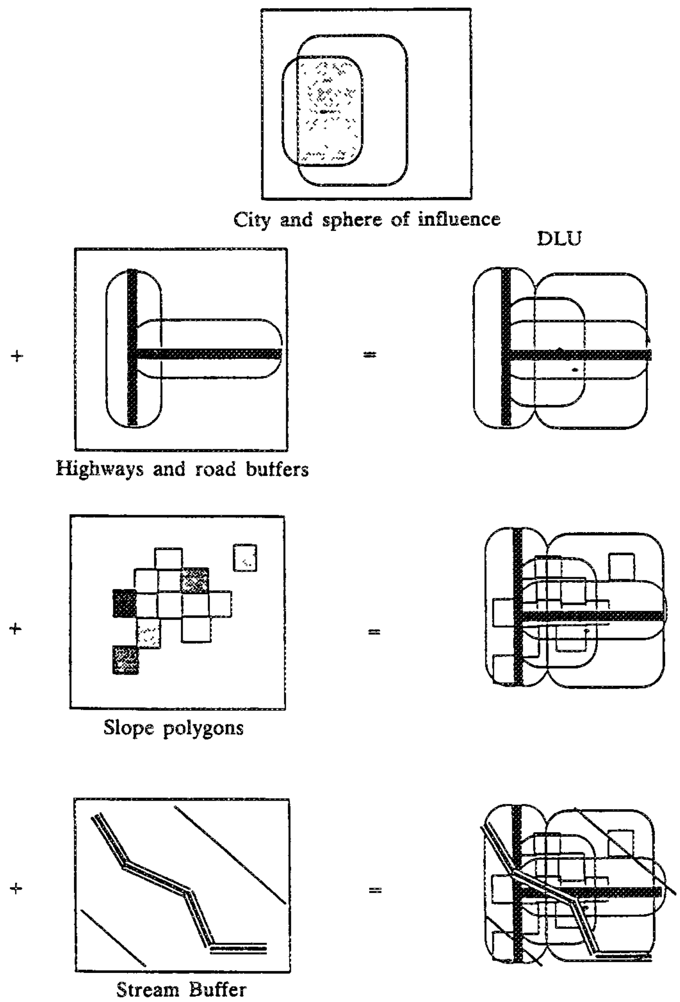

Figure 3. Generation of developable land units (DLUs).

The spatial database currently includes the following map layers and information.

1. *TIGER roads*: As part of the 1990 Census, the Census Bureau digitally encoded maps of major roads and highways in all metropolitan areas. These map files are known as TIGER (Topologically Integrated Geographic Encoded Reference) files. TIGER files can be referenced and projected through a variety of spatial referencing

systems including USGS, UTM, and State-Plane Coordinate. The TIGER roads file, as encoded in ARC/INFO, is the base map layer for the CUF model. It includes federal interstate highways, federal roads, state highways, local arterials, and neighborhood-serving roads.

2. *TIGER census tracts*: TIGER files also include the boundary lines of 1990 Census tracts. The boundaries were assembled into census tracts (polygons) by means of ARC/INFO.

3. *TIGER city boundaries*: the boundary lines of counties and other local governments—including both incorporated cities and unincorporated CDPs. TIGER city boundaries for the San Francisco Bay Region were imported into ARC/INFO, then corrected with updated boundaries supplied by the cities themselves.

4. *TIGER hydrology*: the locations of major streams and water bodies. These were imported into ARC/INFO as a separate layer.

5. *Other TIGER features*: including railroads and airports.

6. *Spheres of influence* (see section 2): Because spheres of influence were originally intended to demarcate each city's ultimate 'build-out' and public service area, they are essential for analyzing possible limits to growth. The size and extent of spheres of influence vary widely by city and county. A map layer incorporating every city's sphere of influence was digitally encoded.

7. *Slope polygons*: Slopes play a major role in determining site developability. Flat and gently sloped parcels are easily and inexpensively developed. As the slope of a site increases, so too does the difficulty and expense of developing it. Sites with average slopes of more than 5% and less than 25% can be developed, but at increasing cost. Sites with average slopes greater than 25% are usually unstable, and are thus rarely developed. To incorporate information on slopes, 500-meter square slope grid cells were generated from US Geological Survey (USGS) topographic maps. Seven sets of grid cells were generated, subsuming the following slope categories: (1) 0% slope; (2) 1-2% slope; (3) 3-5% slope; (4) 6-9% slope; (5) 10-15% slope; (6) 16-24% slope; (7) ⩾25% slope. Adjacent grid cells of similar slope were then merged into slope polygons.

8. *Highway buffers*: Developers favor sites which are accessible through the existing transportation network. To identify relative accessibility, we generated 500 m, 1500 m, and 5000 m polygon buffers around major state and federal highways.

9. *Urban buffers*: Most new urban development occurs at the periphery of existing developments, not in entirely new areas. This is because the cost of extending essential urban services to new undeveloped areas usually outweighs any land-cost savings. To capture this 'adjacency-preference', we generated 1000 m and 2500 m polygon buffers around existing urbanized areas as a map layer.

10. *Earthquake faults*: A California law, the Alquist-Priolo Act, stipulates that structures may not be built on top of a known earthquake fault line. The locations of known earthquake fault lines were obtained from the USGS.

11. *Prime agricultural lands*: Most nonurbanized lands in California currently have some use. In 1988, as part of the California State Farmland Mapping project, the state generated a base map of major agricultural and urban uses. Agricultural use designations are based on current use and soil quality. Agricultural lands are differentiated into: (1) prime agriculture, (2) grazing, (3) forest, (4) of unique state interest, and (5) of unique local interest.

12. *Marsh and wetlands*: All else being equal, development on marsh and wetland areas tends to be costly. This is a result both of the higher costs of site preparation (draining and filling) as well as the added costs of any required environmental mitigation. Moreover, in many areas of California, depending on which agencies have

jurisdiction, intense development may be altogether prohibited from marsh and wetland areas. Digitally encoded maps of wetland and marsh areas for the ten-county San Francisco Bay Area were obtained from the US Fish and Wildlife Service.

13. *Sewer and water utility service costs*: The availability of sewer and water service is an important determinant of site developability. Sites without sewer and water services cannot be intensely developed. Sites inside the service areas of existing water and sewer utility districts can be developed—usually at the cost of extending services to the site. To capture the cost effect, we estimated the straightline distance between each DLU and the nearest already-developed area.

Because these various map layers rarely have common polygon boundaries, the number of DLUs generated by merging the different layers for a single county can easily exceed 20000. Figure 4 illustrates a portion of the merged DLU map for the city of Livermore in Alameda County; table 4 lists a portion of the attributes associated with each DLU.

Table 4. Partial listing of developable land unit attributes.

Developable land unit				Current plan	Maximum density under current plan (persons km $^{-2}$)
no.	area (sq. miles)	perimeter (miles)	acreage	designation	
0	−48447940	25442	0.00		0.00
1	179165	1815	44.27	rural residential	25.00
1	102608	1500	83.43	rural resource	2.08
2	2655	276	0.66	rural residential	83.33
3	4070	312	1.01	intensive agriculture	12.50
4	43419	915	13.70	rural resource	1.04
5	28811	943	7.12	rural residential	83.33
6	1302	323	0.32	intensive agriculture	12.50
7	1049	170	0.26	rural resource	1.04
8	2171	249	0.54	intensive agriculture	4.17
9	25722	697	17.41	rural resource	2.08
10	272931	2418	67.44	intensive agriculture	12.50
11	20312	718	5.02	rural residential	83.33
12	837819	5140	207.03	intensive agriculture	4.17
13	53442	1194	13.21	rural residential	25.00
14	17183	580	4.25	rural resource	2.08
15	14898	1052	3.68	rural resource	6.25
16	6765	392	1.67	intensive agriculture	4.17
17	42892	827	10.60	intensive agriculture	4.17
18	37944	1003	9.38	rural residential	83.33
19	65	39	7.89	rural resourc	2.08
20	4098	318	1.01	intensive agriculture	4.17
21	24675	776	6.10	rural resource	2.08
22	9608	494	2.37	rural residential	25.00
23	23100	945	5.71	rural resource	2.08
24	51027	965	12.61	intensive agriculture	4.17
25	16880	587	119.31	rural resource	1.04
26	79	46	2.41	rural resource	2.08
27	35382	905	8.87	rural resource	2.08
28	20358	950	9.82	rural resource	2.08
29	61504	2189	15.20	rural resource	2.08
30	36562	845	9.03	rural resource	2.08
31	1888	191	0.47	intensive agriculture	12.50
32	98161	1469	24.26	rural residential	83.33
33	104696	1416	25.87	rural residential	25.00

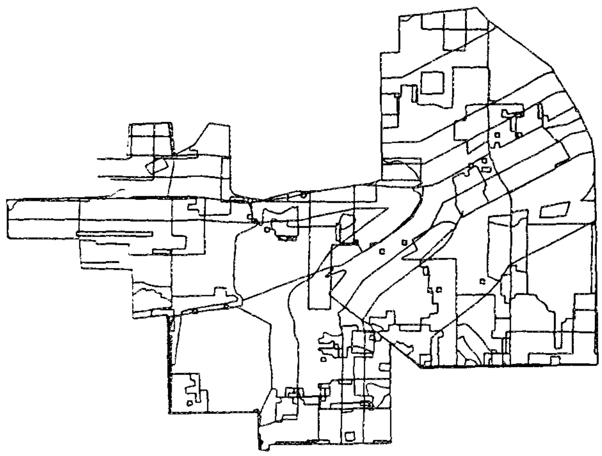

Figure 4. Developable land units in the city of Livermore.

Table 4 (continued).

Publicly owned (0 = no: 1 = yes	Agricultural land type	Current land use	Average slope range (%)	Wetland (0 = no)
0			flat	0
0	developed		flat	0
0	grazing		⩾25	0
0	developed		flat	0
0	locally important		⩾25	0
0	developed		flat	0
0	locally important		⩾25	0
0	grazing		flat	0
0	locally important		⩾25	0
0	grazing		flat	0
0	other		⩾25	0
0	locally important		flat	0
0	locally important		flat	0
0	prime		flat	0
0	prime		flat	0
0	prime		flat	0
0	prime		flat	0
0	unique		flat	0
0	unique		flat	0
0	other		flat	0
0	other		6-9	0
0	grazing	medium-density residential	10-15	0
0	grazing	medium-density residential	10-15	0
0	developed		10-15	0
0	developed		10-15	0
0	grazing		10-15	0
0	grazing		16-24	0
0	grazing	high-density residential	⩾25	0
0	grazing	high-density residential	⩾25	0
0	other	high-density residential	⩾25	0
0	grazing	medium-density residential	⩾25	0
0	other	medium-density residential	⩾25	0
0	developed		⩾25	0
0	developed		⩾25	0
0	developed		⩾25	0

6 The spatial allocation submodel

The spatial allocation submodel is a series of decision rules for allocating projected population growth to appropriate DLUs. In economic terms, the function of the submodel is to 'clear the market': to match the demand for developable sites (as manifest through city and county population growth) to the supply of developable sites (as described by the attributes, size, and location of DLUs).

Unlike most economic models of the development process, this submodel does not work by solving for the land and housing reservation prices that equilibrate supply and demand (Gore and Nicholson, 1991). Rather, it seeks to mimic the way private sector developers evaluate potentially developable sites according to their likelihood of development and ultimate profit potential.

The main assumption behind the submodel is that the location and timing of land-development decisions are mostly in the hands of private land and housing developers, subject to the policy stipulations of state, regional, county, and local governments. We further presume that private housing developers will seek to develop or redevelop sites in order of expected profitability (in accordance with prevailing or permitted development densities), subject to land-use and environmental regulations as imposed by the public sector.

This logic is incorporated into the spatial allocation submodel in the following steps.

Step 1. All undeveloped DLUs in a county are scored according to their potential profitability if developed.

Step 2. Those DLUs that are unsuitable for development for environmental, ownership, or public policy reasons are eliminated from consideration. Examples of DLUs that would not be considered for additional growth might include publicly owned parks and open space, or steeply sloped DLUs having unstable soils.

Step 3. Within each city and its sphere of influence, the remaining DLUs (those that could be developed) are sorted from high to low in order of their potential profitability.

Step 4. Projected population growth for each city is allocated to the DLUs within each city sphere of influence in order of DLU profit potential (high to low); and at population densities consistent with current market conditions, zoning, and general plan requirements, or at 'up-zoned' population densities comparable with other developed areas in the city. After it has allocated as much population growth as will 'fit' into the DLU with the highest profit potential, the model moves to the next most profitable DLU, and so on.

The allocation process within a city is complete either when (1) all projected population growth is allocated, or (2) when there is insufficient undeveloped land in the city to accommodate all forecast population growth. Unallocated population growth, if any remains, is then accumulated for reallocation into unincorporated county areas.

Step 5. The same logic is used to allocate forecast county population growth (plus any unallocated spillover growth from individual cities) to unincorporated county DLUs.

The allocation process within a county is complete either when (1) all forecast and spillover population growth is allocated, or (2) when there is insufficient undeveloped land in the county to accommodate forecast population growth. Unallocated population growth, if any remains, is then accumulated for later reallocation to those counties with remaining developable DLUs.

6.1 Spillover

The potential for spillover development is one of the most interesting aspects of the CUF model. Spillover occurs when there is insufficient developable land in a city or county to accommodate that city or county's forecast population growth. In such cases, the unallocated increment of population growth is accumulated for potential reallocation (or spillover) into a neighboring municipality, unincorporated area, or county. This is not to suggest that it will always be possible to accommodate spillover growth. Depending on the types of local policies being simulated, it may not be possible for the unallocated population growth from one city or area to be reallocated to another city or area.

6.2 Calculating DLU profitability potential

At the heart of the spatial allocation submodel is a procedure for estimating the profit potential of each DLU if developed. Essentially, this procedure casts the computer as a developer, able to estimate the profitability potential of thousands of undeveloped DLUs. The profitability potential of a DLU is the total profit that a homebuilder would expect to realize on the construction of as many new homes as could be accommodated on that DLU. It is calculated as follows:

Per acre residential development profit (i, j, k)
= new home sales price (i, j, k)
− raw land price (j, k)
− hard construction costs (i, k)
− site improvement costs (i, j, k)
− service extension costs (j, k)
− development, impact, service hookup, and planning fees (k)
− delay and holding costs (k)
− extraordinary infrastructure capacity costs, exactions, and impact mitigation costs (j, k).

The index i denotes the size and quality level of the typical new home in each community. The index j denotes the slope, environmental characteristics, and specific location of the homesite (or DLU). The index k denotes the jurisdiction in which the home is located. The individual terms are explained below.

All of the parameters in this model are exogenous. Following economic theory, we assume that homebuilders are *price-takers* with respect to new home sales prices and raw land prices. The costs of extending infrastructure and services to the home site will depend on its location, and, because infrastructure requirements vary by community, the jurisdiction in which it is located. The costs of grading and preparing the site will depend on the size and quality level of the final home to be built, the slope and environmental characteristics of the site, and, as above, the jurisdiction in which the site is located. The costs of constructing the home will vary with its quality and size. Development fees and impact fees usually vary by jurisdiction. Delay and holding costs are more difficult to generalize, but typically vary by jurisdiction. To the extent that extraordinary capacity costs, exactions, and impact mitigation costs can be generalized, they usually vary by project location and jurisdiction.

6.2.1 *Hard construction costs*

Hard construction costs are the costs of building the house, exclusive of the lot preparation costs and the costs of providing the subdivision with urban services. Hard costs vary with the size of the house, the quality of home constructed, and according to the area in which the home is built. Hard costs were estimated for the typical new home in every city and county in the Northern California Bay Region on the basis of median home size and quality, and prevailing construction costs.

6.2.2 *Site improvement costs*
Site improvement costs include the costs of all site preparation up to, but not including, landscaping. Specifically, they include grading, installation of utilities, streetpaving, and the construction of sidewalks, lighting, and gutters. Site improvement costs typically vary with parcel slope, by lot size, and by city. They were estimated for different parcel sizes and slopes with information collected from a survey of regional homebuilders.

6.2.3 *Service extension costs*
For a new development to be served with water, removal of wastewater, storm drainage, cable television, and other utilities, as well as to be accessible to the rest of civilization, developers must build service corridors from existing cities to new subdivisions. Service corridors are usually sized to fit the ultimate capacity of development in the area served. Service corridor requirements and specifications vary widely between jurisdictions, depending on local regulatory experience, fiscal structure, and development preferences. To account for local variations in requirements and costs, we surveyed local public works and engineering departments throughout the region with regard to the number and size of service corridors required to serve noncontiguous subdivisions (that is, subdivisions that were not directly adjacent to existing urban development) of seven different sizes.

6.2.4 *Development and impact fees*
California cities and counties have considerable latitude in their ability to set impact fees[11]. Some fast-growing cities for example charge relatively low fees, while some slow-growing cities charge higher fees. Two separate surveys of impact fees have recently been completed for parts of the study region: one by the Institute of Urban and Regional Development in 1992, and a second survey by the Building Industry Association (BIA) of Northern California.

6.2.5 *Delay and holding costs*
Converting vacant land to residential use entails a variety of costs. To negotiate the administrative process, land developers must pay for studies, permits, engineering, and plans. More significant than these hard costs, however, are the costs imposed by waiting for regulatory approvals. In certain parts of the Bay Area, developers routinely wait more than eighteen months. If these delays are expected, then the cost of holding the land will theoretically be borne by the landowner. The cost of unexpected delays may be borne by the developer, the builder, or the housing consumer. When unexpected delays are common (that is, when approval times are very difficult to predict), builders earn increased risk-associated profits. Delay costs were estimated for each city by calculating the total interest costs (based on a 10% annual interest rate) on raw land associated with time required to secure regulatory approvals (Bay Area Council, 1993).

Specific estimates of each of these cost categories for every city in the study region are reported in Pendall and Landis (1994).

Generally speaking, intracity housing production cost differentials tend to exceed intercity cost differentials. This is because housing production costs vary more according to site slope and distance to urban infrastructure, than according to city. Exactly the opposite is true for profit differentials. Because housing prices

[11] This is not the case, however, for school fees, which were capped by state law in the mid-1980s at $1.56 per square foot for new housing construction. Most cities and counties in the Bay Area now charge this maximum level for residential development.

vary so much between cities, profit differentials tend to vary much more between cities than within them. As an example, figure 5 presents a summary map of land and profit potentials by DLU for Contra Costa County.

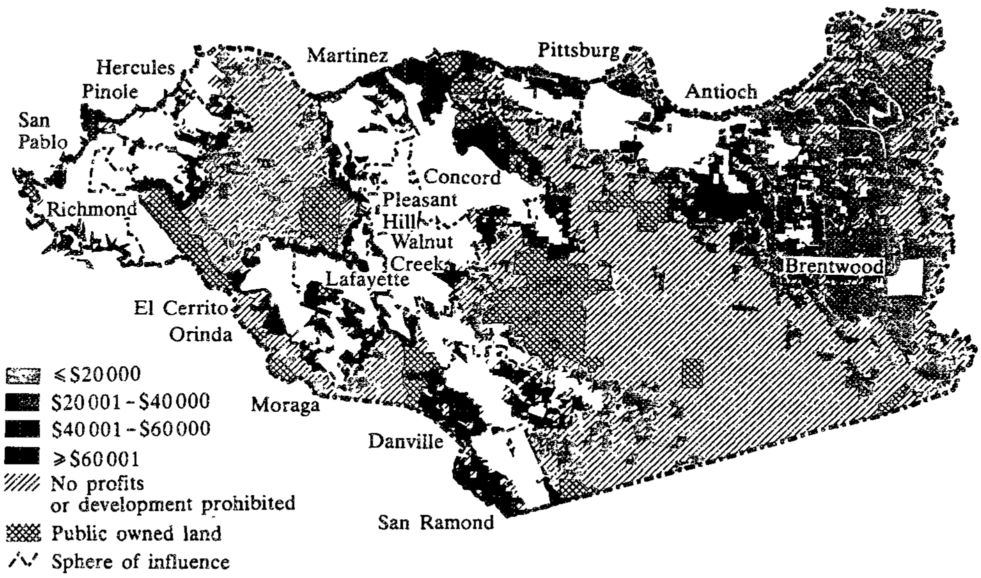

Figure 5. Profit of residential development in Contra Costa.

7 Completing the loop: the annexation-incorporation submodel

The CUF model runs in five-year intervals. By this we mean that population growth is projected and then allocated at five-year intervals. Thus, a twenty-year run of the CUF model is really four sequential five-year runs. There are three reasons why we project in five-year increments. First, the bottom-up population growth submodel was estimated on the basis of five-year increments; to use it for forecasting on anything other than a five-year basis would be inappropriate.

Second, running the model in five-year increments mitigates the possibility that small cities will experience runaway growth. Experience shows that many small cities, particularly those at the urban edge, grow quickly—but only for brief periods. Such cities may experience several years of slow growth before the outward wave of population growth reaches them; followed by several years of extraordinarily high growth rates, as they become the growth wave-front; followed again by several years of moderate growth (as easily developable sites are used up). This cycle of slow growth, followed by rapid growth, followed by moderate growth, may take as many as fifty years, or as few as ten years. Looking only at long-term growth trends tends to even out the cycle or obscure it. As a result, models of small city growth based on ten-year or twenty-year growth trends tend either to underestimate or to overestimate population growth, depending upon where the city is in its growth cycle. As the extraordinary statistical fits obtained in equation 1 would indicate, models of city population growth based on five-year trends tend to do quite well at capturing the small city growth cycle.

Third, from a policy perspective, local land-use policies are often transitory in nature. Few policy initiatives are consistently applied over a twenty-year period. Cities are constantly altering allowable densities and land uses in response to current issues and citizen concerns. Some policies—such as significantly down-zoning developable sites at the urban edge in the face of continued growth pressure—may produce immediate market responses. Other policies, such as extending a mass transit service, may take a generation to affect the spatial pattern of development. Running the CUF model in five-year increments facilitates the simulation of policies that have short-term as well as long-term effects.

Running the CUF model over several sequential five-year periods requires the incorporation of updating loops in the model. This means using the results of the first five-year forecast or simulation as initial conditions for the second set of five-year forecasts, and so on. It also means updating the spatial database to incorporate the specific results of the spatial allocation submodel. If all city boundaries were fixed in perpetuity, the updating process would be straightforward. The first set of outputs of the spatial allocation submodel, a list of newly developed DLUs, would be used to update the spatial database, and the second set of outputs—a city-by-city summary of allocated population growth—would serve as inputs for the next iteration of the bottom-up population growth forecasting submodel.

In reality, city boundaries are ever-changing. The traditional practice is for cities to extend their boundaries (almost always by annexing unincorporated county lands) to provide a higher level of public services to growing areas, in order to increase their tax base, and to improve the integration of newly developing areas with already developed neighborhoods. More recently, many cities in California have been extending their boundaries outward (and thus their control over land uses) as a way of preventing or reducing development. Still other cities have chosen not to extend their boundaries in the face of citizen pressures as a way of retaining their existing community character.

Annexation is not the only way California cities can expand. Previously unincorporated neighborhoods can, through incorporation, become cities. Neighborhoods incorporate for the same reasons that cities expand: to capture a tax base, to facilitate orderly development, to obtain a higher quality of local public services, and, on occasion, to prevent new development.

Because city boundaries (and spheres of influence) are so essential a part of the CUF model, the updating process must necessarily include a procedure for determining which newly developed DLUs are to be annexed to existing cities and which are to be part of newly incorporating cities. Making such determinations is the purpose of the annexation-incorporation submodel.

At this stage of its development, the annexation-incorporation submodel consists of a simple regression model comparing 1980-90 annexation activity by city according to city population, density, location, and growth policy. The sample upon which the model is estimated excludes 'landlocked' cities (that is, those unable to expand their boundaries) but includes cities that could have annexed but did not.

Coefficient estimates and goodness-of-fit measures for the annexation submodel are presented in table 5. ANNEXACRE(i; 1980-90), the dependent variable, is the number of acres annexed in city *i* between 1980 and 1990. Only two independent variables are statistically significant: CHNGPOP, the change in city population during the previous ten years, and COUNTY GROWTH CONTROL, a dummy variable indicating whether or not county growth policies formally restrict annexation. Both coefficients are of the expected sign: population growth encourages city annexations, whereas county-growth limits slow them. Two other independent variables, INIT-DENSITY (the density of each city in 1980), and CITY GROWTH CONTROL (a dummy variable indicating whether a city had adopted a population or housing unit growth cap), were not found to be statistically significant. Subsequent efforts will be made to refine this model and to develop a companion model for projecting incorporation activity.

Table 5. Regression results of the ten-county annexation model.

Independent variable[a]	Estimate of coefficient	t-statistic	β-value
CHNGPOP	0.217	9.56	0.75
COUNTY GROWTH CONTROL[b]	−950.50	−1.964	−0.15
INIT-DENSITY	not statistically significant		
CITY GROWTH CONTROL[b]	not statistically significant		
Constant	965.73	2.67	
R^2	0.61		
F-statistic	49.66		
Standard error	1968.16		
N	67		

[a] The dependent variable is ANNEXACRE(i; 1980–90): the acres annexed in city i during the previous ten years (sample excludes landlocked cities). The independent variables are defined in the text.
[b] Dummy variables with values 0 or 1.

8 Simulating development policy changes

The effects of new regulatory and investment policies upon the location, amount, and intensity of urban development can be simulated in the CUF model through three different mechanisms.

8.1 Adding new spatial features or map layers

Adding new features or map layers changes the geometry and characteristics of the set of DLUs—the supply side of the CUF model. For example, to simulate the likely impacts of a proposed greenbelt, one would first generate a new map layer showing its precise location. This new layer would then be merged with the existing set of DLUs. The updated DLU list would then indicate which particular DLUs were inside or outside the greenbelt. Such information would be used within the spatial allocation submodel either to prohibit development within greenbelt DLUs, or alternatively, to reduce the densities of development in greenbelt DLUs. To the extent that the greenbelt DLUs would have otherwise been allocated more development, that development would then be reallocated elsewhere.

8.2 Changes in environmental or infrastructure policies that facilitate (or prohibit) development, or alter the cost of development

Changes in environmental and infrastructure policies can affect the allocation of growth to individual DLUs in three ways. First, such policies can affect the calculation of the profitability of developing a particular DLU or set of DLUs. For example, the decision not to expand a municipal water district to service a growing city would tend to make development in that city more expensive, thereby reducing its attractiveness to private housing developers. Raising local development fees in certain cities would have a similar effect.

Second, policy changes can affect which DLUs are precluded from development. For example, the adoption of a county-wide policy to prohibit development on steep hillsides would eliminate steeply sloped DLUs from development consideration regardless of their private development profit potential.

Third, policy changes can affect the densities at which new development is allocated. For example, rather than totally prohibiting development from prime agricultural lands, a county government might reduce the maximum development densities allowed on such parcels. Such a change would create a density ceiling for such DLUs, as well as reduce the profitability of developing them.

8.3 Changes in local zoning and/or land-use regulations

City and county governments frequently up-zone and down-zone areas, as well as change allowable uses. Such policy shifts can be simulated in two ways. First, previously undevelopable DLUs can become developable (and vice versa). This would be the case when land parcels previously reserved for commercial development are opened up to residential development.

Second, changes in local land-use policies will affect the profitability potential associated with specific DLUs. This, in turn, will affect the order and densities at which new development is allocated. For example, the effect of down-zoning one side of a city would be: (1) to reduce the relative profitability of DLUs on that side of the city, thereby reducing the attractiveness of that side of the city; and (2) to limit the amount of new development which could be allocated to that area.

Because every DLU is identified as being in a particular city or county, the CUF model can be used to simulate policy changes that arise at the local (city) level, at the county level, or at the regional level (across counties).

9 Directions for further development

The current version of the CUF model is still only a prototype and significant developmental work remains to be done. Our agenda for future model development is organized into six different work areas:

1. *Better incorporation of regional and local accessibility measures* The current version of the CUF model does not directly incorporate measures of accessibility into either the bottom-up growth forecasting submodel, or into the spatial allocation submodel. This presents both theoretical and practical problems. On the theoretical side, accessibility to employment opportunities, shopping opportunities, and recreational opportunities is widely recognized to be one of the most important determinants—if not the single most important determinant—of long-term development patterns. On the practical side, the lack of accessibility measures in the CUF model makes it difficult to use the model to simulate the spatial and development impacts of major transportation pricing and investment decisions. The next iteration of the CUF model will incorporate various measures of accessibility into both the growth-forecasting and growth-allocation steps.

2. *Improved treatment of infill development and urban redevelopment*[12] The current version of the CUF model assumes that almost all population growth will occur at the urban edge. The possibility of small-lot 'infill' development and redevelopment is not included in the spatial allocation submodel. This is in part because of the lack of a reliable inventory of infill parcels and redevelopment opportunities, which makes it difficult to simulate the likely impacts of policies designed to promote infill and redevelopment. The next iteration of the spatial allocation submodel will include both components.

3. *Improved treatment of different housing forms* The current version of the CUF model considers housing only in terms of housing units per acre. It does not distinguish between single-family detached housing, attached housing, and multifamily housing. This makes it difficult to simulate the impacts of public policies that concern specific forms of housing. A future version of the CUF model will forecast

[12] Infill refers to the development of currently vacant parcels that fall inside already developed cities. Redevelopment refers to the development of newer, different, or more intense uses on parcels that are currently developed.

the growth of single-family housing units separately from the growth of multifamily housing units. Similarly, there will be different allocation procedures for single-family and multifamily housing.

4. *Development of an employment growth and allocation submodel* County-wide basic employment change is currently exogenous to the CUF model. As a result, it cannot be used to simulate the likely effects of local economic development policies, or the spatial implications of major employment shifts. Future versions will include procedures for forecasting basic employment, and for allocating employment at the subcounty level.

5. *Development of linkages to available transportation and air quality models, as well as fiscal impact models* The outputs of the CUF model (the specific locations and densities of new urban development) are also the inputs into regional transportation and air quality models, as well as local fiscal impact models. Future versions will include links to these other models.

6. *Incorporation of household income, composition, and ethnic heritage into the model* The current version of the CUF model does not distinguish between different types of population growth. For example, the growth of high-income households, or Hispanic households, or single-parent households is not distinguished from the growth of low-income households, or African-American households, or elderly households. This is an unfortunate oversimplification. Whether for reasons of preference, or because of the existence of mobility barriers and discrimination, not all household types have the same housing opportunities. The reality is that any growth and development policy has strong implications for social and economic equity. To the extent possible (and subject to the availability of appropriate data), a future version will incorporate the various location preferences (as well as the different growth rates) of different income, age, and ethnic groups.

10 Summary

The CUF model is the first of what we hope is a new generation of metropolitan simulation models. It responds to the need for practical, theoretically consistent tools that can be used to simulate the spatial implications of realistic urban growth and development policies, and it breaks new ground in four separate areas. First, on the demand side, it considers the process of population growth from a bottom-up perspective; that is, by assuming that population growth in individual cities responds to local growth policies in addition to regional population and employment growth pressures. Second, through the use of a GIS, it uses a variety of map layers to describe the environmental, political, and economic conditions which determine the developability of particular sites. Third, it allocates forecast population growth to particular sites on the basis of a series of transparent decision rules that mimic how private developers actually make land-development decisions. Fourth, it explicitly models patterns of annexation and incorporation. Although the coefficient estimates for the various models included in the CUF model are unique to the San Francisco Bay Area, the concepts behind those models, and the linkages between models are widely applicable.

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