Using these guidelines, the Hartford experience can serve as a useful model for approaching similar transportation problems in other cities.

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Urban Development Models for the San Francisco Region: From PLUM to POLIS

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ABSTRACT

Most of the operational urban development models were designed 15 years ago and do not reflect the planning concerns of the 1980s. PLUM (Projective Land Use Model), the land use system developed for the Bay Area in 1970, suffers from conceptual and operational limitations that hinder its use. A new model, which is structurally and behaviorally different from the traditional Lowry models, was designed at the Association of Bay Area Governments. The new model, referred to as POLIS (Projective Optimization Land Use Information System), is based on microeconomic behavioral principles; it is formulated as a mathematical programming problem and considers job location, housing selection, and trip making in an integrated fashion.

Urban modeling is the science that attempts to represent in mathematical terms the location and interactions of activities within a metropolitan urban environment. The origins of the field can be traced back to the early 1960s when the growing problems of cities and the widespread use of automobiles in every aspect of everyday life necessitated the development of analytical tools that could assist planners in evaluating policy alternatives and predict and prescribe the future.

A transportation planning process that focused on comprehensive planning and long-range capital investments for transportation facilities, coupled with a massive increase in federal assistance to state and local governments, led to the design of urban development models for several metropolitan areas during the period 1960-1975. The vast majority of these models were developed in planning agencies rather than academic environments and had ambitious goals. It was widely believed that models could be used for comparing the effects of alternative transportation networks; for controlling and directing urban growth; and for analyzing urban redevelopment plans, the existence of racial ghettos, and problems of poverty and housing deterioration (1,2).

The failure of the models to meet the initial grandiose goals resulted in a backlash for urban modeling. As planners gained experience, they realized that models could not solve the urban problems and became critical of the use of models in planning. Lee (3) proclaimed that large-scale models are dead, whereas the empirical work of Boyce (4) and Pack (1), who studied the actual experience of planning agencies, showed that urban models had minimal impact on policy and decision making.

Critics of urban modeling were correct in pinpointing the limitations of the early models, but failed to notice that most of these arose from either the overambitious expectations about the role of models in planning or the general lack of knowledge about the state of the art and the capability to implement successfully complex mathematical equations. They did not provide an alternative methodology that could address some of the more modest goals and potential applications of large-scale models (consistent set of forecasts, evaluation of alternative transportation improvements).

As a result of the reversal of attitude toward models, few, if any, models have been developed for metropolitan areas in the last decade. Urban modeling research has been carried on at the universities, often at a theoretical level, or abroad, mainly in England, while planning agencies continued using the models of the 1960s without any improvement or modification. However, local governments and planning agencies are still faced with the issues that led to the massive application of models before 1975. There is still a need to disaggregate regional population and employment totals among smaller spatial units; there is still a need for a consistent set of forecasts that could permit a local government to plan for capital improvements and a regional agency to carry out evaluation of new projects (A-95 review). Finally, because of the limited availability of capital, there is a greater need now to analyze thoroughly the impact of alternative transportation improvements.

Today, planning agencies are attempting to answer these questions with models that are 20 years old. Most of the operational models are descendents of the work of Lowry (5) in 1964 and the 1965 early version of EMPIRIC (6). These models represent the planning concerns of their time, concerns that were different in scale and scope from today's problems. They describe an urban environment with a population composition, economic structure, and geographic distribution significantly different from the one that exists today. Accordingly, they cannot be used to answer the problems of today. The mere recalibration of these models with recent data is not enough because they are based on socioeconomic assumptions that are no longer valid. Planning needs of the 1980s must be addressed by procedures that recognize the key behavioral and economic issues that influence the location of households and firms.

Reported in this study is the experience of the Association of Bay Area Governments (ABAG), the planning agency of the San Francisco region, with the implementation of POLIS (Projective Optimization Land Use Information System), a land use and transportation model that is behaviorally and structurally different from the models used in the past. PLUM (Projective Land Use Model), the ABAG land use modeling system in the 1970s, is reviewed along with its limitations. The rationale behind the new model and its mathematical structure are discussed and the potential applications of the model for planning are outlined.

THE ABAG MODELING SYSTEM IN THE 1970s

The history of land use models in ABAG goes back to the early 1970s when the Series 1 projections for the Bay Area were developed based on the PLUM model. The PLUM model, one of the most widely known variants of the Lowry model, was first developed in 1968 at the Institute of Transportation and Traffic Engineering of the University of California by a research team led by William Goldner (1). It was adopted by ABAG and through time became synonymous with the ABAG modeling system. During the period 1970-1978 it was calibrated for several metropolitan areas and underwent a series of changes at ABAG and the San Diego Comprehensive Planning Organization. Most of the changes altered the outputs of the model but not its internal structure.

The PLUM modeling system consists of two major models that operate in sequence, BEMOD (Base Employment Model) and PLUM. The former provides an allocation of basic employment to place-of-work zones. The employment allocations from BEMOD are then used to "drive" PLUM, which locates population, housing, and local serving employment and accounts for the land absorbed and the land use constraints. In addition to these two models the system contains a myriad of utility models that prepare the inputs and disaggregate the outputs of PLUM by income, housing structure, type, and so forth.

The most recent implementation of BEMOD in the Bay Area recognizes 14 industrial groups. Through a modified shift-share process, regional totals for these sectors are partitioned among the four Standard Metropolitan Statistical Areas (SMSAs). Within SMSA, zonal employment allocations are made on the basis of regression equations developed from a cross-sectional analysis of 1964 data. The independent variables include the size of vacant industrial area, the amount of developed basic land, the zonal share of county employment in the base year, and physical characteristics such as mean elevation, presence of water frontage, and so forth. When applying the model to project future employment levels the coefficients of the regressions are held constant.

The spatial allocation of households and local serving employment in PLUM involves a three-step process. First, the changes in basic employment derived from BEMOD are allocated to residential locations by a probability function describing the willingness to commute. Then, based on these residential allocations and the location of basic employment, demand for population serving employment is estimated. Home-to-shop and work-to-shop probability functions are used for that purpose. The third stage of PLUM checks for violation of any land use constraints. Any zonal residential demand exceeding land supply is reallocated to the nearest zone with available land.

The PLUM modeling system has several shortcomings that limit its usefulness for the planning needs faced today in the San Francisco Bay Area. There are serious conceptual limitations that arise from the assumptions embedded in the system. The most significant of these are described next.

1. The model disregards to a great extent the interaction between jobs and housing. It assumes that changes in housing location patterns do not

affect the location of industries. This might be true for the traditional heavy manufacturing sectors but does not apply to "footloose" industries. Intraurban locational decisions of these firms are influenced by the availability of a qualified labor force and the presence of agglomeration economies rather than the amount of capital invested in the past, the magnitude of transport costs, and environmental concerns. The electronics, research and development, finance, insurance, and real estate (FIRE), and business services sectors, which constitute the most prominent, and fastest growing segment of the Bay Area economy, are typical examples of footloose industries.

2. The model overemphasizes the importance of the traditional basic sectors (agriculture, mining, manufacturing transportation) in the economy. Employment in these sectors is allocated first and assumed to be the dynamic element in the economy. However, with the rapid transformation of the economy from one centered in heavy manufacturing to one driven by industries with high technology and financial products, the basic/nonbasic partitioning does not fully describe the dynamics of the different sectors. In the Bay Area, high-technology-related jobs are expected to double in the next 20 years, FIRE employment is expected to increase by almost 50 percent, while traditional manufacturing (SIC 20-34, 37) will experience a growth of only 20 percent in the same period.

3. The PLUM system as formulated lacks a behavioral interpretation. It describes the urban system as it exists in the base year without attempting to explain the decision making at the micro level. Residential choice is simulated by a function that replicates aggregate trends, but does not address the decisions of the individual household searching for a house. The allocation algorithm for the industries is based on established patterns and not on some economic concept such as profit maximization. This approach disregards the behavioral aspects of every locational and trip-making decision and can be of limited use in environments undergoing changes in the sectoral composition of employment, household size, labor force participation rates, and the amount of land available for development.

4. The model represents the transportation system in simplistic terms. There is only one mode, and generalized travel costs are defined to be equal to travel time. None of the behavioral techniques for modeling the travel to work or the travel to shop behavior is utilized.

5. The model cannot easily handle planning and zoning constraints. The allocation algorithm for housing and local serving jobs operates sequentially through the zones in zone-number order. Land constraints are addressed at the end of each iteration, at which point overflows are reallocated in the next iteration. This procedure often distorts the results of the model because overflows are allocated to distant zones because all the nearby zones are filled (7).

In addition to the conceptual limitations, the San Francisco version of PLUM suffers from several operational problems that hinder its use. The zonal system (440 zones) is not homogeneous and zones vary substantially in size, population, and housing characteristics. The 440 zone system, which was initially specified to facilitate detailed traffic analysis, is very disaggregate for 20 years' projections. At this level of detail the model's output is so large that the planner cannot properly evaluate it, and the modeling process is a number-crunching nightmare.

The other major operational problem with PLUM is the sheer size of the computer code. PLUM was originally written in 1968-1970 and has never undergone a complete revision. Over the years different users have made changes and modifications on an ad hoc basis, most of which are not documented. The original code has more than tripled and is now unmanageable. The procedure for running the different programs is so cumbersome that it can take 2 to 3 weeks to complete a full run of the model.

FRAMEWORK FOR A NEW MODEL

The PLUM system was used during the 1970-1980 period to generate three sets of projections (Projections 1, Series II, and Projections '79). When preparing for the next round of projections in 1982, it became obvious that the shortcomings of PLUM were too serious and could not be corrected. PLUM had grown to be a dinosaur and contained assumptions that were outdated. The experience with the latest set of projections in 1979 had also indicated that some of the zonal forecasts of PLUM were often inaccurate. It was then decided to abandon the complete PLUM system and construct a new model that could be useful in conducting strategic planning for the 1980s.

As a first step in developing a new system, a thorough analysis of the objectives and constraints of the modeling process was carried out. In order to avoid the disillusionments of the early land use models, it should be clear from the beginning what the model is expected to perform and the constraints that are imposed by limited resources and our knowledge of the state of art. To accomplish the former, the Bay Area economy was studied to pinpoint the planning concerns of the next 20 years and to define the important variables and interactions that the model must consider. This analysis led to the following conclusions that guided the overall modeling process.

1. The model should simulate the interaction between jobs, housing, and regional transportation systems and should provide a consistent description of the future patterns of development.
2. The primary use of the model will be for prescriptive purposes; that is, to produce projections, reconcile forecasts with local jurisdiction's constraints, and to balance jobs and housing.
3. Because the model could at some time in the future be used for policy impact analysis, it should be sensitive to the variables that are affected by changes in policy, namely, provision of housing, location of large development projects, and construction of new transportation facilities.
4. The model must have a behavioral interpretation and must be based on economic concepts (utility maximization, profits).
5. Local planning and zoning constraints are very significant in the development process and should be explicitly considered by the model.

Because our efforts were not supported by a research grant, two resource constraints were imposed: (a) the new modeling system must be developed in-house and should be operational in less than 12 months, (b) the data required for calibration should be readily available from the 1980 Census, or from ABAG's data base. These two constraints played a crucial role in the design of the new model, and the final form and structure of the model is an attempt to meet the guidelines and objectives under the resource constraints.

The outcome of the modeling effort was the design and calibration of POLIS for the Bay Area. POLIS is a land use-transportation model that allocates employment and housing at the subregional level and estimates commuting flows and shopping trips. It is different from the traditional, Lowry-type land use models in three key respects: (a) it is based on microeconomic behavioral principles; (b) it is formulated as a mathematical programming problem; and (c) it considers job location, basic and nonbasic employment, residence selection, and trip making in an integrated fashion.

STRUCTURE OF THE MODEL

The allocation process in POLIS is based on several criteria, some reflecting the behavior of the locators and some describing the physical and planning constraints imposed on a growing urban region. Residential choice is determined by the travel-to-work and shopping behavior, the availability and inherent attractiveness of housing, and the existence of nearby employment opportunities. Retail activity is located in proximity to population centers to maximize sales revenue. The profit maximization and cost minimization objective of the different industries is translated into locational patterns influenced by the accessibility to labor supply, the existence of agglomeration economies, and the interindustry relationships.

In a drastic departure from the long history of operational land use models, which are formulated as a system of equations whose solution can be carried out only through an iterative procedure, POLIS is cast within the framework of mathematical programming. In this framework, decision variables are optimized with respect to prespecified goals while satisfying the planning constraints. The use of mathematical programming to describe the urban system has advantages and disadvantages. The major disadvantage is that it results in a complex mathematical notation and solution procedure; the major advantage is that residences, employment, and trip flow patterns are estimated in a single iteration and are consistent with each other and the land use constraints. There are no overflows of activity to be reallocated, and the final solution is not sensitive to the sequence in which zones have been numbered.

The main difficulty in designing an optimization land use model is the specification of the objective function. Because the results of the model must describe the most probable land use configuration at some future time, the objective function must reflect goals that are widely accepted to govern the formation of cities. In a free economy system the plurality of decision making makes it difficult to define a unique objective. Earlier attempts to build normative models failed because they used objective functions which, at best, could be considered as partial representations of reality. For example, the objectives of cost minimization and overall efficiency in the works of Schlager (8) and Mills (9) are not realistic because they presuppose the existence of some authority regulating all growth activity.

In the proposed model the objective function is defined by invoking the framework provided by random utility theory (10,11). The fundamental premise of random utility theory is that an individual faced with a set of alternatives will choose the one that maximizes his or her utility or surplus. Accordingly, the appropriate objective for an urban growth model is the maximization of the total locational surplus. The surplus can be interpreted as the total net benefits arising from a specific plan or policy, and its maximization reproduces the individual behavior at an aggregate level.

The functional form of the locational surplus can be obtained by analyzing the choice mechanisms the model is expected to simulate. In POLIS, activity patterns are affected by locational decisions of two decision makers: individual selecting a job and a nearby house to live in, and firms choosing the site to locate new employment opportunities. The job-housing choice is reduced to a simple residential choice because intraregional wage differential for the same type of job is often insignificant. Residential choice is assumed to be influenced by (a) the location of workplace, or more correctly, the duration of the travel to work trip; (b) the mode of travel to work; and (c) the shopping behavior of the individual. Invoking the formalism of random utility theory (12), it can be shown (13) that in this case total locational surplus or benefits are given by

$$
\begin{aligned}
Z(T_{ijm}, S_{ij}) = & \left\{-(1/\beta^{w}) \sum_{ijm} T_{ijm} \left[\ln \sum_{m} T_{ijm}/W_i \ -1\right]\right\} \\
& + \left\{-(1/\lambda) \sum_{ijm} T_{ijm} \left[\ln T_{ijm} - 1\right] - \sum_{ijm} T_{ijm}\, c^{w}_{ijm}\right\} \\
& + \left\{-(1/\beta^{s}) \sum_{ij} S_{ij} \left[(\ln S_{ij}/W^{s}_{j}) - 1\right] - \sum_{ij} S_{ij}\, c^{s}_{ij}\right\} \qquad (1)
\end{aligned}
$$

where

T_{ijm} = number of work trips from i to j by mode m,
c^{w}_{ijm} = travel cost of the work trips from i to j by mode m,
S_{ij} = number of shopping trips from i to j,
c^{s}_{ij} = travel cost from i to shopping activities at j,
W_i = nonlinear transformation of the utilities interpreted as an indicator of the attractiveness of zone i for residential choice,
W^{s}_{j} = nonlinear transformation of the utilities interpreted as an indicator of the attractiveness of zone j for shopping, and
β^{w}, β^{s}, λ = parameters converting the utility associated with trip making into monetary units compatible with the transportation costs incurred.

The first two components of Z define the locational surplus attached to residential choice when considering only work trips; the multiple dimension of the decision process associated with work trips results in two surplus functions: one for destination and one for modal choice. The last component depicts the contribution of the shopping behavior in the total surplus.

The maximization of the locational surplus Z, in addition to describing individual trip making and house-seeking behavior, results in location patterns for retail activities that are consistent with the profit maximization principle. By maximizing the accessibility of consumers to shopping establishments, the accessibility of shops to potential customers and therefore the expected revenues are also maximized.

The location of nonretail industries is integrated in the mathematical framework by adding to the objective function the factors influencing their locational decisions. For the sectors dominating the Bay Area economy (electronics, research and development, finance, and services), it is assumed that the two most important factors are access to qualified labor and existence of agglomeration economies. The first factor is already part of Z; the surplus function represents the locational benefits of the employees with respect to their travel-to-work behavior; hence, it maximizes the accessibility and interaction between labor supply and labor demand.

Agglomeration economies arise from the propensity of firms to locate adjacent to each other in order to take advantage of some common resources. When several firms locate in the same area, they cumulatively create an environment that induces growth and facilitates business. Access to sources of capital, labor market economies, proximity to suppliers and competitors, access to specialized business services, and superior training facilities are some of the components that are referred to as agglomeration economies.

Because these economies cannot be easily quantified or estimated, the proposed model uses surrogate variables to simulate their impact. Two types of agglomeration economies can be discerned: those occurring at the zonal level and those exhibited at the macro (county) level. The former stem from the inherent attractiveness of small areal units and are directly related to zonal characteristics such as relative cost of land and accessibility to other employment centers. The latter consist of the causal relationships that link activities to each other and represent comparative advantages and profitabilities arising from the existing structure of production. The intersectoral relationships shown by the input-output table and the tendency of certain industries to locate in specific counties are the most significant ones.

Zonal economies are incorporated in the objective functions by adding the component

$$\sum_{i,k} f^k_i(\cdot)\, E^k_i \tag{2}$$

in Z, where $f^k_i(\cdot)$ is a function of some zonal characteristics and represents the agglomeration potential of zone i for sector k and E^k_i is employment of the same zone and sector. Macro economies are integrated in the model by adding equations in the constraint set, which show the spatial sectoral relationships for each county and sector. These equations take the form

$$E^k_{co} = a + b\, E^k_{co,t-1} + \sum_{q\epsilon Q} c_q\, E^q_* \tag{3}$$

where subscripts co and t-1 denote, respectively, county and lagged variables E^q_* is total regional employment in sector q to be allocated among the different counties, and Q is the set of sectors with which industry i has strong economic relationships.

The objective function represents the joint surplus of the individuals seeking homes and firms locating new employment. It does not include any component related to the limited availability of land because land restrictions are not part of an individual's behavior. In an environment that has unlimited development potential, locators locate so that their surplus is maximized. If, however, land constraints do exist, then locators might be forced to select second best choices. In the POLIS framework, the issue of limited availability of vacant land is handled easily by specifying constraints that limit the development in certain zones.

POLIS simulates the changes between two states. At each time period only the new increase in employment opportunities and households is allocated, and relocation of base-year jobs is handled by appropriately increasing the number of jobs to be distributed. The total number of jobs and housing to be allocated is given exogenously and is derived from regional economic models.

The complete mathematical representation for POLIS is as follows:

$$\begin{aligned}\max Z(T_{ijm}, S^k_{ij}, \Delta E^n_j, \Delta H_j) = (-1/\beta^w) \sum_{ij} T_{ijm} &\left[\ln\left(\sum_m T_{ijm}/W_i\right)\right. \\ &\left.-1\right] - (1/\lambda) \sum_{ijm} T_{ijm}\left[\ln T_{ijm} - 1\right] \\ &- \sum_{ijm} T_{ijm}\, c_{ijm} - \sum_{k\epsilon K} (1/\beta^S_k) \\ &\sum_{ij} S^k_{ij}\left[\ln(S^k_{ij}/W^k_j) - 1\right] - \sum_{ijk} S^k_{ij}\, c_{ij} \\ &+ \sum_{i,n\epsilon K} (f^n_i)^{an}\, \Delta E^n_i\end{aligned} \tag{4}$$

subject to

1. Origin-destination constraints for work trips T_{ijm}. Work trips out of a zone are related to the number of households through a trip generation rate a_i

$$\sum_{jm} T_{ijm} - a_i(H^o_i + \Delta H_i) = 0 \tag{5}$$

Work trips in a zone are related to employment through a trip attraction rate b^n_j

$$\sum_{im} T_{ijm} - \sum_n b^n_j(E^{no}_j + \Delta E^n_j) = 0 \tag{6}$$

2. Origin-destination constraints for shopping trips S^k_{ij}. Shopping trips out of a zone are related to the number of households through a trip generation rate e^k_i

$$\sum_j S^k_{ij} - e^k_i(H^o_i + \Delta H_i) = 0 \tag{7}$$

Shopping trips in a zone are related to retail employment through a trip attraction rate h^k_j

$$\sum_i S^k_{ij} - h^k_j(E^{ko}_j + \Delta E^k_j) = 0 \tag{8}$$

3. Land use density constraints for employment and housing. Available land limits the number of jobs and households to be allocated in a zone

$$\sum_n d^n\, \Delta E^n_j \leqslant \bar{L}_j \tag{9}$$

$$\Delta\bar{H}_{i,lb} \leqslant \Delta H_i \leqslant \bar{V}_i \tag{10}$$

4. Allocation of all employment and housing. All regional employment and housing units must be allocated

$$\sum_j \Delta E^n_j - \bar{E}^n_* = 0 \tag{11}$$

$$\sum_i \Delta H_i - \bar{H}_* = 0 \tag{12}$$

5. Spatial-sectoral constraints for county employment. Employment in one sector is related to employment in other sectors

$$\sum_{j\epsilon P_c} \Delta E^n_j - \sum_{q\epsilon Q} \sum_{j\epsilon P_c} c^q\, \Delta E^q_j - y^n_c = 0 \tag{13}$$

6. Exogenous location of employment and housing (policy constraints). A priori allocate a certain number of jobs and housing units in some zones

$$\Delta H_{i,lb} \leqslant \Delta H_i \tag{14}$$

$$\Delta\bar{E}^n_{j,lb} \leqslant \Delta E^n_j \leqslant \Delta\bar{E}^n_{j,ub} \tag{15}$$

$$T_{ijm}, S^k_{ij}, \Delta H_i, \Delta E^n_j \geqslant 0 \tag{16}$$

where

S^k_{ij} = number of shopping trips from zone i to service activities of sector k in zone j,
ΔE^n_i = number of new jobs for sector n in zone i,
ΔH_i = number of new housing units (households) in zone i,
$\bar{L}_j$ = area of land available for employment growth in zone j, and
$\bar{V}_i$ = vacant residential land in zone i.

Most of the constraints are self-explanatory. With the coefficients e^k_i denoting mean expenditures per per household, the flow variables S^k_{ij} can be interpreted as volume of sales. The two land use constraints (9,10) can be combined if there are no restrictions on the type of development that can occur in an area. Finally, the constraints (Equations 14-15) have been added to handle the exogenous location of large development projects. By appropriately specifying the lower bounds, the model can be used to evaluate the systemwide effects of these projects.

The number of trips can be obtained by considering the Lagrangian function. It can be shown (Equation 13) that at optimality trip flows are equal to

$$T_{ijm} = A^w_i H_i B^w_j E_j \exp(-\beta' \tilde{c}_{ij}) \\ [\exp(-\lambda c_{ijm})/\sum_m \exp(-\lambda c_{ijm})] \tag{17}$$

$$S_{ij} = A^s_i H_i B^s_j E^s_j \exp(-\beta^s c^s_{ij}) \tag{18}$$

where A^w_i, B^w_j, A^s_i, and B^s_j are the balancing factors, β' is a transformation of β, and λ and $\tilde{c}_{ij}$ is the composite travel cost between i and j given by

$$\tilde{c}_{ij} = (1/\lambda) \ln \sum_m \exp(-\lambda c_{ijm}) \tag{19}$$

The expression for the trip flows is the well-known nested logit model similar to the one derived from a behavioral analysis at the micro level. This is another indication that, although POLIS is formulated at the aggregate (macro) level, results in spatial interaction patterns are consistent with individual behavior.

POLIS can be estimated in two different ways. The first approach is to use a standard nonlinear programming algorithm to estimate the dual problem of Equations 4-16. It is easier to solve the dual instead of the primal because the former has a significantly smaller number of variables and constraints. The second approach is to exploit the structure of the primal and solve the model by applying the Bender's Partitioning Algorithm. Although the direct solution is preferable, the current version of POLIS employs the partitioning solution method because the author did not have access to a nonlinear programming algorithm at the time the model was first designed.

ESTIMATION AND CALIBRATION OF POLIS

The complete land use transportation model was calibrated for the San Francisco Bay Region using data from two different time periods, 1975 and 1980. The empirical estimation relied only on already available data; no major data collection effort, such as a household survey or a special tabulation of census data, was undertaken. Different sources of information were used, and as a result, the data were often inconsistent. The major sets of data used were:

1. 1975 distribution of jobs and housing and complete land inventory (available at ABAG);
2. 1980 distribution of jobs and housing (available from the 1980 Census);
3. 1975 detailed (440 zones) travel-to-work trip tables by mode and level of service characteristics--travel time, distance, value of time (available from the Metropolitan Transportation Commission);
4. 1980 aggregate (30 zones) shopping trips table;
5. 1975-1980 development activity and 1980 development potential for every zone;
6. 1980 household soicoeconomic characteristics (available from the census).

For the purpose of the model the 9 counties of the Bay Area were divided into 107 zones, each representing an aggregation of census tracts. Two modes, automobile and transit, and four employment sectors were recognized. The four sectors were:

1. Manufacturing;
2. Transportation, Finance-Insurance-Real Estate;
3. Retail Trade; and
4. Services

The implementation of the model in the Bay area consisted of three major tasks: estimation of the attractiveness weights and agglomeration economies function, specification of the spatial sectoral equations (Equation 13) and complete calibration of the model to determine the values of β^w, β^s, λ, and α^n. Because POLIS has a complex structure and because there was no information on 1980 travel-to-work trip flows, the seven parameters could not be calibrated simultaneously. An alternative procedure was devised and the model was calibrated in three stages. A complete discussion of the calibration process can be found in The Land Use Information and Transportation System for the San Francisco Bay Region (13).

To evaluate the ability of the model to forecast accurately, the calibrated model was used to forecast the 1980 location of housing and jobs; 1975 was the base year. The goodness-of-fit statistics of these forecasts with the actual 1980 data are tabulated in Table 1. The goodness-of-fit of both the total values and the incremental 1975-1980 changes are reported.

Overall the statistics depict a fairly good fit. The R^2 for total housing and for each of the employment sectors are all between .85 and .91. The figures for total employment and housing, .89 and .90, respectively, indicate an almost perfect fit. These high values might arise from the fact that the model allocates only the total regional change, which, for the 1975-1980 period, does not exceed 35 percent of the employment and 20 percent of the in-place housing.

The fit of the model when comparing the forecasts with the actual 1975-1980 change was also acceptable. The R^2 for housing and employment drops to .74 and .78. There is a wide variation in the fit of the different sectors. Retail Trade is the sector with the best fit (.82), whereas transportation and FIRE exhibits the worst fit (.64). The fit of the basic sectors is on the average less successful than that of the retail and service sectors. This may be attributed to several factors; for example, it is

TABLE 1 Results of the Calibration Goodness-of-Fit of Predictions With Actual 1980 Data

	R^2
Housing units	
Total	.90
1975-1980 change	.74
Total employment	
All sectors	.89
Manufacturing	.90
Transportation, FIRE	.84
Retail trade	.91
Services	.85
1975-1980 employment change	
All sectors	.78
Manufacturing	.75
Transportation, FIRE	.64
Retail trade	.82
Services	.74
Trips to work (1975)	
Total	.79
Automobile	.81
Transit	.69

possible that the zonal agglomeration functions were not defined or calibrated correctly, or that some of the factors influencing locational decisions of basic industries were ignored. Additionally, some errors are introduced by the way some sectors are defined; the sector of transportation and FIRE includes employment groups that do not have the same locational characteristics. The fit of total employment is superior to that of most of the individual sectors, a sign that the model captures the aggregate locational patterns.

An interesting aspect revealed by the goodness of fit statistics is that the model is more successful in predicting total employment than housing. Housing that was not disaggregated by ownership type or quality characteristics--price range, age, number of units in structure--has a fit that is not as good as the one for total employment. These results indicate that extensions in the model should be in the area of disaggregating housing by type and introducing supply equations linking supply and demand.

Only the fit of the travel-to-work trips is reported because there was not a detailed trip table for shopping trips. The fit of the work trips is not as good as expected. In aggregate transport studies, R^2 in the range of .85 to .95 are not uncommon. However, it should be kept in mind that the model was calibrated to reproduce the 1980 distribution of housing and employment and not necessarily the trip table for 1975. The R^2 obtained after the first stage of the calibration process, when the parameters were calibrated to reproduce the 1975 trip tables, were close to .90. Finally, the generalized costs and values of time were taken from another study and might not be the appropriate ones for the proposed model.

POTENTIAL PLANNING APPLICATIONS OF THE MODEL

A major reason for building a new land use information system for the San Francisco area was the need to provide a tool that could be useful in strategic planning. The Bay Area economy is undergoing a series of structural changes that will have significant repercussions on the utilization of the transportation network, the differential growth of various communities, and the adoption of zoning policies. Some of the issues that can be addressed by POLIS include:

- The impact of changes in local policies regarding land development;
- The impact of accelerated shifts in regional employment from manufacturing to research and development, finance, and services industries; and
- The impact of investments in the transit system, such as the proposed extension of BART, on the location of housing and employment.

The first issue is related to the development policies of the different cities and counties of the Bay Area. A community's development policies include general and specific plans and other programs to either encourage or discourage development activity in an area. Local zoning regulations for the type and density of new developments, capital improvement schedules, and building permit allocation are some of the methods used to manage the rate of growth.

The different land use policies of local government can be used to define the supply of land available for accommodating future households and employment activities. Their impact can be easily simulated by POLIS because land constraints are explicitly considered in the model. Policies imposing lower densities for new residential units can be directly translated into number of acres available for development or potential housing units, and their citywide and regionwide impacts on housing location can be tested. More important, because the model addresses the issues of housing supply and employment location in a systematic fashion, the impact of the policies restricting housing growth or the number of jobs attracted in the affected areas can also be simulated.

The second issue, change in the sectoral composition of employment, can have profound effects on the character of the Bay Area. The new industries have locational patterns and labor force requirements that are in several aspects different from those of traditional manufacturing. They are characterized by an increasing emphasis on decentralization and product specialization, reliance on the availability of a well-educated labor force, and diminishing requirements for large initial capital outlays. All of these might result in considerable shifts in population and employment. Employment in areas that traditionally have been considered to be "dormitory towns" are suddenly swelling because of the rapid increase in the number of self-employed individuals and the formation of many small companies with specialized products, computer software, for example.

The emerging tendency in some industries to locate the office close to the homes of the employees might lead to a substantial divergence in the growth rates of the current central business districts (CBDs) and the peripheral areas; eventually, this will have important repercussions on the transport network utilization. Traffic volume on the CBD-bound highways and transit systems might remain steady or even decline. In the peripheral areas--Central Contra Costa, Solano, and Sonoma counties--where the automobile is often the only available mode of transportation, the congestion on the highways might lead to chaotic situations.

POLIS has the capability to simulate the impact that changes in the composition of regional employment will have at the local level and can assist in the evaluation of the various policy alternatives. Employment is disaggregated in four sectors and can be further disaggregated should the need for a more detailed analysis arise. Transportation is integrated in the framework, and trip-flow matrices for different growth scenarios can be computed and policy implications can be derived.

Finally the last issue, evaluation of investments in transportation infrastructure, is the issue for which the majority of the land use models have traditionally been designed. Investments in the transportation infrastructure alter the accessibility of certain areas, which, in turn, induce locational shifts. Additionally, as noted earlier, the change in the locational patterns might lead to an increased demand for transport in areas where the infrastructure is inadequate. It must be acknowledged that because of the relatively high level of aggregation of the transport network, the model does not lend itself to the simulation of minor transportation investments, for example, highway interchanges, rather it lends itself only to major additions to the system. The proposed extensions of the BART system and the provision of improved transit services in the high growth areas are examples of investments whose impacts could be tested by POLIS.

CONCLUSION

In the last 10 years the field of operational urban models has been in a stagnant state. Disillusionment with the early applications of the Lowry model has led most public agencies to abandon efforts to build urban development models. To this author's knowledge, POLIS is the only comprehensive land use-transportation model implemented for a metropolitan area of the United States in the last 10 years. The calibration of the model for the Bay Area points out that meaningful models can be calibrated despite data availability and limited resources constraints. Finally, the successful use of POLIS for producing long-range subregional forecasts for the Bay Area is an indication that large models can be useful for planning purposes if cast in the appropriate framework.

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