

# Incremental Cooperative Development of Land Use Models in California

John E. Abraham<sup>1</sup>, John Douglas Hunt<sup>2</sup>, Robert A. Johnston<sup>3</sup>, Michael McCoy<sup>3</sup>,  
Shengyi Gao<sup>3</sup>, Eric Lehmer<sup>3</sup>

<sup>1</sup>HBA Specto Incorporated, Calgary, AB, T2P 3P4, Canada

<sup>2</sup>University of Calgary Institute for Sustainable Energy, Environment and Economy

<sup>3</sup>University of California at Davis ULTRANS Center

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## Abstract

Integrated land use and transport planning models are being developed for the state of California in the USA as well as for the major cities in California. These are being developed to improve planning and plans in the state, in particularly in response to recent legislation requiring that planning models and analytical techniques be able to assess the effects of policy choices on land use, auto ownership, vehicle- miles traveled, and on-road greenhouse gases (GHGs). The Sacramento model was developed first, and is now on its second iteration of development. The San Diego model benefitted from the experience in Sacramento, with major improvements in the analysis of micro-level location choices in hedonic rent models. The California model dealt with state-wide data inconsistencies, and built a 50m by 50m base parcel layer of building type and building intensity by applying a synthetic allocation approach. The California modeling effort improved calibration techniques for adjusting the dispersion parameters and constants in the underlying logit models. The Los Angeles and San Francisco models began as training efforts for agency staff, with pared-down versions of the statewide model.

In 2010 the agencies responsible for the 5 models continue to communicate and work together to further the behavioral representation in the models and the development of the open-source software (called PECAS) that implements the models. Major efforts in 2010 include re-estimating local rent effects from statewide data, adjustments to the representation of land developers to take into account the elastic capacity of the construction industry, incorporating an explicit representation of greenhouse gas production and energy use, a flexible system for representing changing land-use regulations (zoning) and construction costs over time and location, direct integration with spatial databases and hence more immediate visualization possibilities, and a general improvement in input data quality, in particular with regard to economic interactions and land characteristics.

## **Background**

In California, the interaction between land use and transportation has long been recognized. Recent legislation focusing on greenhouse gas (GHG) reductions from the transportation sector has mandated land use planning for transportation greenhouse gas reductions.

The Global Warming Solutions Act, Assembly Bill 32 (AB32) specifies the target for GHG emissions in 2020 as the 1990 level of GHG emissions. Senate Bill 375 (SB375) – commonly known as ‘California’s anti-sprawl bill’ – mandates regional GHG targets linked to land use plans and transportation policies. This implicitly acknowledges the view (Ewing 2008) that GHG reductions from the transportation sector can only be met by changing the way communities grow, switching from low-density auto-oriented development to compact development. The scoping plan for AB32 places emphasis on SB375 and tentatively calls for a five million metric ton reduction in CO<sub>2</sub> equivalents annually by 2020 from land use and transportation planning. GHG targets are to be phased in beginning in 2012. However, prior to the implementation of these targets, AB32 requires analysis of their economic and equity effects.

The development of integrated land use and transportation policy analysis models in California was underway before SB375 was drafted and passed (Abraham, Garry and Hunt 2005) (Thorne, et al. 2006) (Beardsley, et al. 2009), reflecting a general willingness in California to analyze transportation policy and land use policy using a consistent system of analysis. But the legislative requirements have provided an additional incentive to local planners, and now numerous models are under development and/or in operation. The models include five models described here, as well as models following the UP framework (Johnston, Shabazian and Gao 2003) (Johnston, McCoy, et al. 2004) (Beardsley, et al. 2009) (Thorne, et al. 2006) and a model of the City and County of San Francisco (the central area of the San Francisco urban region) using the Urbansim framework (Waddell, Wang and Charlton 2008).

The Production Exchange Consumption Allocation System (PECAS) (Hunt and Abraham 2009) is a mathematical system for representing economic spatial interactions and land development patterns. It is designed to provide a simulation of the evolution of built form and spatial economics over time, with a focus on the response of the system to transportation policy and land use policy. The state of California and the 4 largest urban regions in California are developing PECAS models to analyze policy and forecasts for both land use and transportation, focusing on the interaction between land use and transportation, the resulting impact on GHG emissions, and the economic and equity impacts. PECAS is implemented in open-source software that has been developed for and with the agencies that use it.

## **Overview of the PECAS modeling system**

PECAS includes two basic modules that are linked together with two other basic modules to provide a representation of the complete spatial economic system.

The set of four basic modules includes:

- Space Development module (SD module): This is one of the two PECAS modules. It represents the actions of developers in the provision of different types of developed space where activities can locate, including the new development, demolition and re-development that occurs from one point in time to the next. This developed space is typically floor space of various types and is called “space” in the PECAS framework.
- Activity Allocation module (AA module): This is the other of the two PECAS modules. It represents how Activities locate within the space provided by developers and how these Activities interact with each other at a given point in time.
- Transport Model (TR module): This is one of the “non-PECAS” modules. It represents the transport system connecting locations, including at a minimum a transport network, the transport demands that load onto this network (as a result of the economic interactions represented in the AA module) and the congested times and costs for interactions between locations arising with the loading of these demands.
- Economic Demographic Aggregate Forecasting Model (ED module): This is the other of the “non-PECAS” modules: It is some form of model or approach used to develop aggregate economic forecasts for the study area being modeled. Typically, these forecasts include projected numbers of households or population by category and employment by type (as indications of expected economic activity) for specific points of time in the future.

The four basic modules listed above are linked together with information flows as shown in Figure 1. This linked system works through time in a series of discrete, fixed steps from one point in time to the next, with the AA module running at each point in time and the SD module considering the period from each point in time to the next. The fixed steps are typically one-year time steps to allow an appropriately quick response of land developers in the SD module to the space prices established in the AA module.

Ideally, the transport model (TR module) used to calculate the congested travel times and associated transport utilities is run for each year, after the AA module has been run for that year. If the overall model run times are too long and travel conditions are relatively stable, the TR module can be run less often to save computation time.

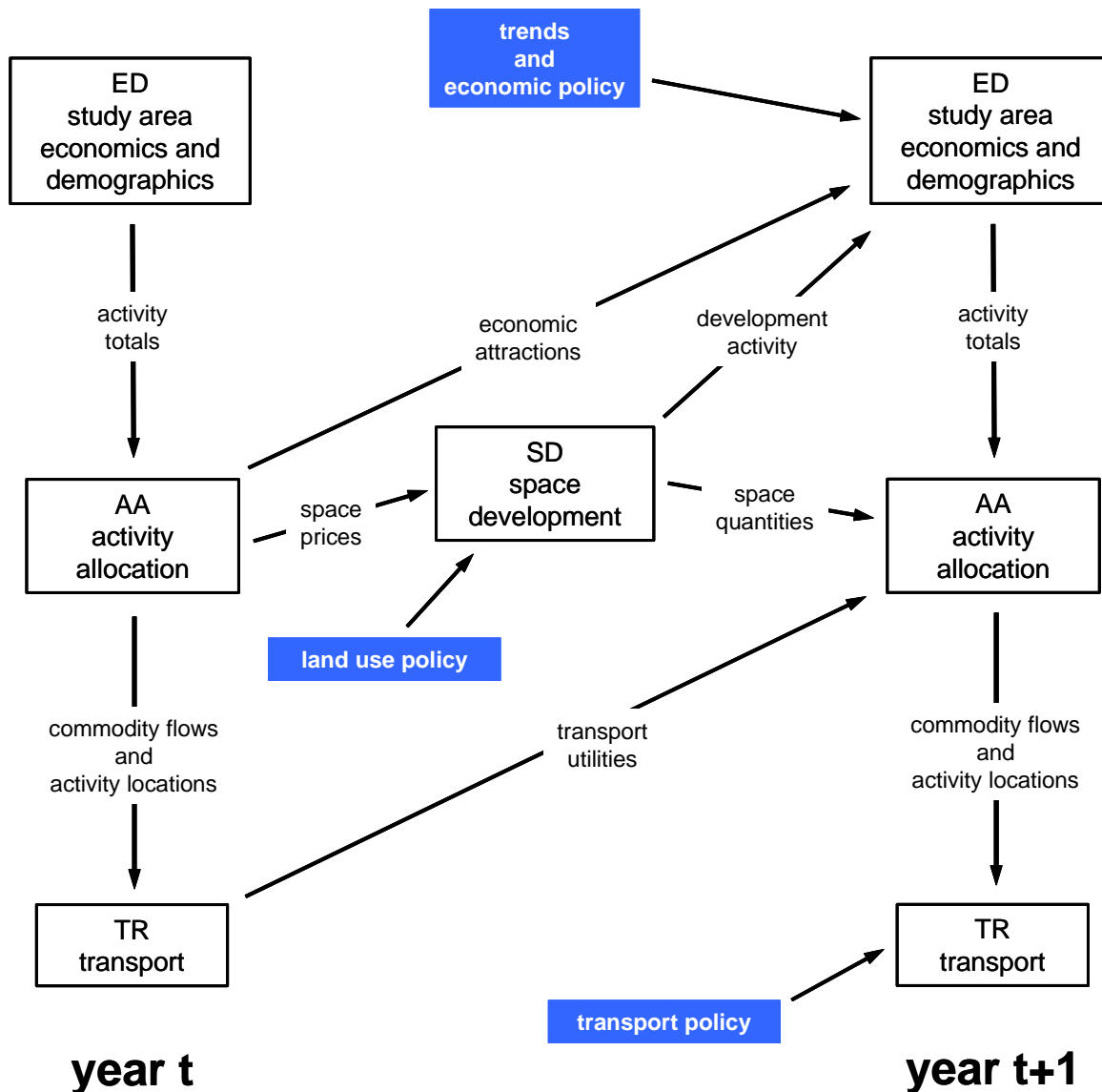


Figure 1: The operation and interdependencies in a PECAS modelling system

The study area is organized into a set of land use zones (LUZs). In the AA module Activities locate in these zones and Commodities flow between them. These zones match the transport zones (TAZs) used in the TR module or are aggregations of whole numbers of adjacent TAZs. The connectivity among the LUZs is based on the representation provided by the TR module, where the TR module establishes congested network times and costs and associated transport utilities that the AA module uses in its consideration of the interactions between the LUZs in the next time period.

The land in each LUZ is further partitioned into smaller cells or parcels. The parcels can correspond to actual legal parcels or portions of legal parcels. The cells can be formed by superimposing a grid pattern over the land. The term “parcel” is used to refer to both cells and parcels in the descriptions below. In the SD module, developed space (called “space”) is located on these parcels, with only one type of space on a given parcel, and

the total quantity of each type of space in the LUZs is the sum of the quantities on the parcels in the LUZs.

### ***Activity Allocation module***

The Activity Allocation module (AA module) is an aggregate representation. It concerns quantities of activities, flows of commodities and markets with aggregate demands and supplies and exchange prices.

Activities are located in LUZs. Activities produce commodities and then transport and sell these commodities; they also consume commodities after buying them and transporting them. Industrial production establishments and households are grouped into activity categories, and other activity categories represent government, financial or institutional operations. The AA module allocates the study-area wide quantity of each activity among the LUZs as part of its allocation process.

Commodities flow at specific rates from where they are produced by activities to where they are exchanged (from seller to buyer), and then from where they are exchanged to where they are consumed by activities. Commodities are grouped into categories, including different types of goods and services, labor and space. Commodities other than space in general flow across zone boundaries. Space is restricted in that it is "non-transportable" and must be exchanged and consumed in the LUZ where it is produced – which means that the space commodity categories receive some special additional treatments in PECAS as described further below. The movement of these flows of commodities from where they are produced to where they are consumed is the economic basis for travel and transport in the modeling system. It is the travel conditions – the distances, costs, times and associated (dis)utilities by mode – for the movement of these commodities that results in the influence of the transportation system on the interactions among activities and the attractiveness of locations for activities. The AA module allocates the flows of commodities from production location LUZ to exchange location LUZ and from exchange location LUZ to consumption location LUZ, and finds the corresponding set of prices at the exchange location LUZs that clears all markets, as part of its allocation process.

Activities produce commodities and consume commodities in the production process according to the technology they use. More specifically, an activity quantity in a given LUZ produces commodities at specific rates per unit of activity and consumes commodities at specific rates per unit of activity according to the technology being used by the activity. One or more "technology option" alternatives are defined for a given activity. Each of these technology options is a specific vector of production and consumption rates for different commodities per unit of the activity, representing a particular technology option for the production process available to the activity. The AA module allocates the quantity of the activity in each LUZ among these "technology options" as part of its allocation process.

The allocation process in the AA module uses a three-level nested logit model with a nesting structure as shown in Figure 2.

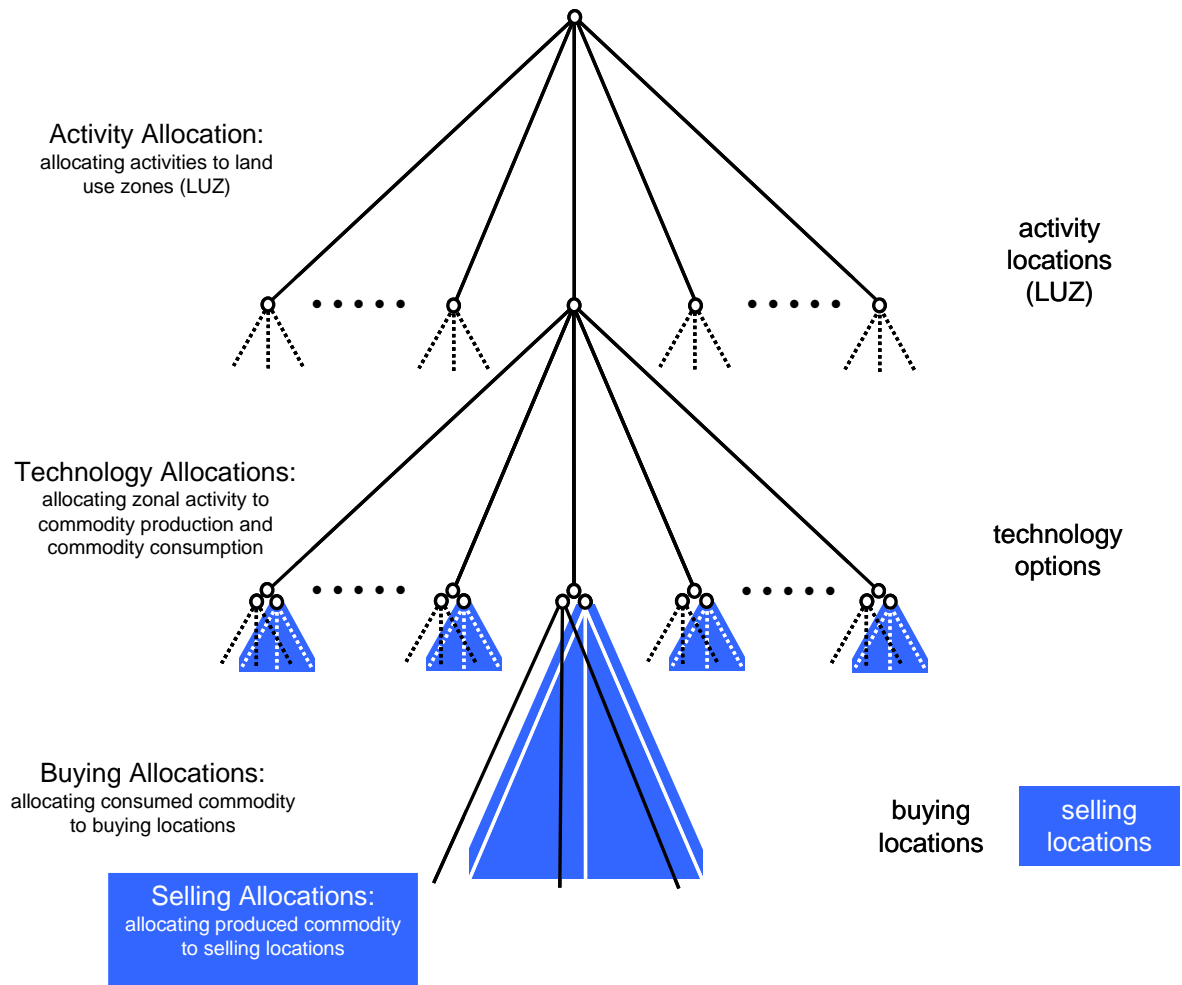


Figure 2: Three-level nesting structure used in AA module allocations

At the highest level of the nesting structure, the study-area total quantity of each activity is allocated among the LUZs. At the middle level, the quantity of each activity in each LUZ is allocated among the available technology options. At the lowest level, there are two logit allocations for each commodity in each LUZ: The first is an allocation of the produced quantities among the various exchange locations where they are sold to other activities; the second is an allocation of the consumed quantities among the various exchange locations where they are bought by other activities.

At the lowest level, the utility of each exchange location alternative is influenced by the price at the exchange location and the characteristics for transporting the commodity to or from the exchange location. The composite utility values from these two lowest-level logit models are called the “buying utility” and the “selling utility” for the commodity in the LUZs. They are used as the transportation-related inputs in the middle-level for allocating the activities in the LUZs among the relevant technology options. The composite utility value for the range of technology options considered at the middle-level for an activity in an LUZ is part of the location utilities used at the highest-level.

The spatial aspects of the AA module allocation process are illustrated in Figure 3. Buying and selling allocations link through the exchange locations to establish commodity flows from production to consumption locations in the LUZs.

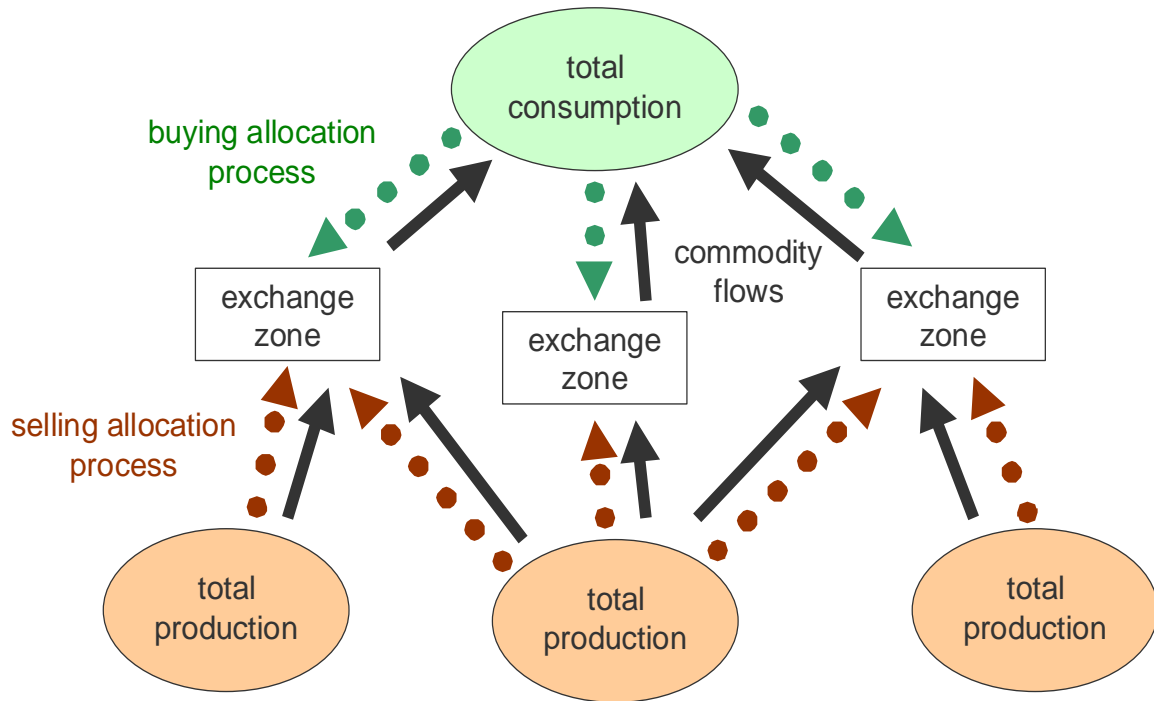


Figure 3: Buying and selling allocations resulting in commodity flows from production zone to consumption zone via exchange location

The exchange locations are location-specific markets for commodities, where sellers sell commodities to buyers. Prices are established at exchange locations so that the quantity bought equals the quantity sold – thus the spatial allocation procedure in the AA module assumes a short-run market equilibrium in commodities.

### *AA Utility Equation*

Since AA is based on random utility theory, it is based on a “utility function” describing the attractiveness of each option implied in Figure 2.

For one unit of activity type  $a \in A$ , where  $A$  consists of the full set of types of activity under consideration, including households, business establishments, and other institutions, consider the joint choice of:

- Location,  $l \in L$ , that is the home location for the unit; being residential location for households, or establishment location for business establishments and other institutions (the top level of Figure 2);



- Technology Option,  $p \in P^a$ , described by a set of technical coefficients  $\alpha_p = \{\alpha_{p1}, \alpha_{p2}, \dots, \alpha_{pn}, \dots, \alpha_{pN_p}\}$  and a corresponding list of commodities  $c_p = \{c_{p1}, c_{p2}, \dots, c_{pn}, \dots, c_{pN_p}\}$ , each  $c_{pn} \in C$ . Each  $\alpha_{pn}$  describes how much of commodity  $c_{pn}$  is produced (or consumed, if  $\alpha_{pn}$  is negative) per unit of activity  $a$ , with indices  $n$  from 1 through  $N_p$ .  $P^a$  is the set of allowed Technology Option alternatives for activity  $a$  (the middle level of Figure 2); and
- Exchange location,  $e_n \in E_c$ , for each commodity  $c_{pn}$  produced or consumed, being the choice of where to purchase, sell (or otherwise exchange as is the case for unpriced commodities) the quantity  $|\alpha_{pn}|$  (the bottom level of Figure 2).

The utility of this joint choice is given by:

$$U_{lp e_1 e_2 K e_n}^a = V_l^a + \varepsilon_l^a + V_p + \varepsilon_{lp} + \sum_{n=1}^{N_p} |\alpha_{pn}| s_{pn} (V_{e_n l} + \varepsilon_{e_n lp}) \quad (1)$$

where:

- $V_l^a$  = the measurable component of utility associated with the location  $l$  and activity  $a$
- $\varepsilon_l^a$  = a random component of utility associated with location  $l$  and activity  $a$
- $V_p$  = the measurable component of utility associated with the technology option  $p$
- $\varepsilon_{lp}$  = a random component of utility associated with the technology option  $p$  and location  $l$
- $\alpha_{pn}$  = the technical coefficients associated with technology option  $p$  as described above
- $s_{pn}$  = scaling adjusting associated with technical coefficient  $\alpha_{pn}$  (non-negative and usually 1.0)
- $V_{e_n l}$  = the measurable component of utility associated exchanging the commodity  $c_{pn}$  associated with  $\alpha_{pn}$  in exchange location  $e_n$  given location  $l$  and technology option  $p$
- $\varepsilon_{e_n lp}$  = a random component of utility associated with exchanging the commodity  $c_{pn}$  at exchange location  $e$  given activity location  $l$  and technology option  $p$ .

The terms  $V_p$  and  $V_l^a$  are normally established in calibration, and do not change between years or between scenarios. Thus the core policy-sensitivity of the model is in the  $V_{e_n l}$  terms. Each of the  $V_{e_n l}$  terms contains three subterms:

- the disutility of transporting commodities to or from the exchange zone,
- the prices of commodities in the exchange zone, and
- the relative size of the exchange zone.

Since prices are determined endogenously to clear the spatial markets, the dominant policy-related inputs to AA involve transport costs and measures of zone size (normally quantities of space from SD), and the total quantity of each activity specified as a policy control total to be allocated according to equation 1 and Figure 2.

See Hunt and Abraham (Hunt and Abraham 2005) and (Abraham and Hunt 2007) for complete documentation of the theoretical formation and calibration methods of the PECAS model.

### ***Space Development Module***

The Space Development (SD) module is a microsimulation of the changing built-form state of individual parcels (or grid cells). SD represents the decisions made regarding a unit of land by the people who own or control the land.

The SD module of PECAS is a sort of cellular automata (CA) model with explicit elements of economic theory, with the following characteristics:

- The potential function is divided into two parts, an expected rent revenue calculation and a construction cost calculation.
- The expected rent revenue calculation is based on the zonal average rent established in the supply/demand interaction in the AA Module, modified by specific demand elements that apply at the sub-zonal level (the “local level effects”).
- Cadastre (parcel) divisions of land are supported along with grid based representations (a regular grid is not required since the complex calculation of rent potential is performed separately in the AA Module)
- The state transition is Monte Carlo sampled based on a logit framework, incorporating a random uncertainty in the future state,
- There is also a sampling of intensity of use.

These characteristics bring the SD module in line with urban economic theory, where space is provided by land owners in response to the willingness-to-pay for space of the tenants (DiPasquale and Wheaton 1996). Bringing more economic theory into CA models has been suggested as being useful for long range high-resolution spatial forecasting (White and Engelen 2000).

The SD Module simulates the transitions that can occur among space types, with the transitions classified as shown in Figure 4.

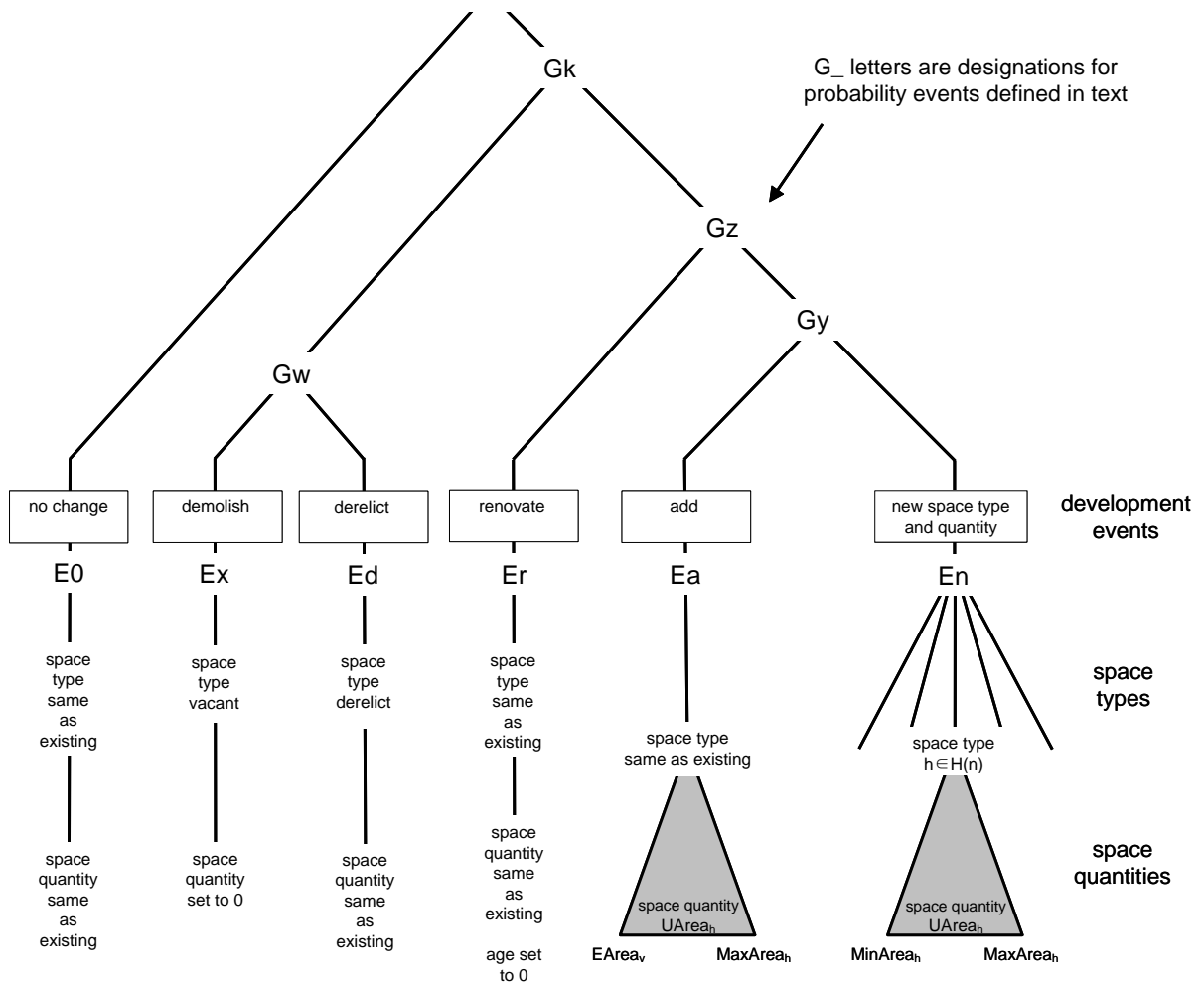


Figure 4: Nested logit model structure for development event probabilities

The SD module processes the parcels in a random order. For each parcel first the set of options in Figure 4 is reduced to account for 1) the existing state of the parcel (for instance it is impossible to undertake demolition on a parcel that is already vacant), and 2) the restrictions imposed by zoning regulations or other land use policy (for instance, some space types may not be allowed on the parcel).

Once the set of options have been established, the SD module calculates the attractiveness of each of the options.

The attractiveness of an elemental option is essentially the rent minus the amortized construction costs minus maintenance costs, so that developers are attracted to options where future revenue exceeds the costs of transitioning to that option. The current status is included as the “No Change” alternative, so that the opportunity costs of departing from the current state is also present in the comparison.

For instance, for a particular intensity option under a “new space type  $h_i$ ” alternative, the utility is

$$NetRev_{v,h} = (Rent_h - TrCostsS_{v,h} - MtCostsS_h) \cdot j - l \cdot (TrCostsL_{v,h} + \varepsilon_s + \varepsilon_q + \sum \varepsilon_n) \quad (2)$$

where:

- $NetRev_{v,h}$  = expected net revenue for transitioning from existing space type  $v$  to updated space type  $h$  on parcel per unit of updated space type  $h$ ; in units of money per unit of area for space type  $h$  per year;
- $Rent_h$  = expected rent for updated space type  $h$  on parcel per unit of updated space type  $h$  in units of money per unit of area for space type  $h$  per year;
- $TrCostsS_{v,h}$  = amortized money cost for transitioning from existing space type  $v$  to updated space type  $h$  on parcel per unit of updated space type  $h$ . Typically this is the amortized construction unit cost for updated space type  $h$ , in units of money per unit of area for space type  $h$  per year;
- $MtCostsS_h$  = maintenance money costs for updated space type  $h$  on parcel per unit of updated space type  $h$  in units of money per unit of area for space type  $h$  per year, for brand new space (maintenance costs increase with structure age, but this option is to build new space);
- $TrCostsL_{v,h}$  = amortized money cost for transitioning from existing space type  $v$  to updated space type  $h$  on parcel per unit of land on parcel in units of money per unit of land per year;
- $j$  = amount of space under consideration;
- $l$  = size of parcel in units of land;
- $\varepsilon_s$  = a random component of utility associated with the space type alternatives  $S$  ( $b \in S, h \in S$ );
- $\varepsilon_q$  = a random component of utility associated with the continuous quantity alternatives;
- $\varepsilon_n$  = random components associated with the top three levels in Figure 4;

SD integrates equation 2 over the available intensity options (the values permitted for  $j$  by the zoning regulation, indicated by  $MinArea_h$  and  $MaxArea_h$  in Figure 4) and calculates the expected maximum value of all of the continuous intensity options as the utility of the “new space type  $h_i$ ”. Assuming the random variable  $\varepsilon_q$  is Gumbel distributed gives a closed form solution for the expected maximum that eliminates the  $\varepsilon_q$  random variable. Assuming Gumbel distributions for various combinations of the  $\varepsilon_s$  and  $\varepsilon_n$  random terms allows closed form probability functions to be calculated, and used together with a random number generator in a Monte Carlo process, to select a particular outcome from among the options in Figure 4 for each parcel. See (Hunt, Abraham and De Silva, et al. 2007) and (Hunt and Abraham 2009) for an explanation of these assumptions and integrations.

### Rents

The expected rent for each updated space type  $h$  on the parcel,  $Rent_h$ , is calculated taking into account the zonal-level price established for the current year in the AA Module and local-level effects due to the density of development around the parcel, the distance from (or proximity to) local-level influences, and the age of the existing space on the parcel, if any, as follows:

$$Rent_h = Price_{h,z} \cdot \prod_{g \in G} LEFac_{g,h} \quad (3)$$

where:

- $Rent_h$  = rent for updated space type  $h$  on parcel; in units of money per unit of area for space type  $h$  per year, in equation 2;
- $Price_{h,z}$  = price for updated space type  $h$  determined in AA Module for current year; in units of money per unit of area for space type  $h$  per year;
- $g$  = index of local-level effects on rent
- $G$  = set of all local-level effects on rent considered
- $LEFac_{g,h}$  = factor adjusting proportional change in rent for space type  $h$  as a function of values on dimension relevant for local-level effect  $g$ .

The  $LEFac_{g,h}$  terms allow the rent on a particular parcel to be dependent on the attributes of the parcel, in particular the age of the space on the parcel, and how near the parcel is to various landscape features that would make the location within the LUZ more or less attractive to the occupiers of space type  $h$ , separate from the general travel accessibility that is included in the  $Price_{h,z}$  term calculated within AA. Local level effect landscape features typically include local schools, freeways (which cause noise and other negative externalities), freeway ramps (which provide access to a freeway and hence reduced travel times), local parks and beaches or other bodies of water, and the density of development in the immediate area.

### *Transition Cost representation*

The representation of construction costs follows three different types of GIS layers. There are layers for the *physical costs* of construction, layers for the *fees* associated primarily with jurisdictional boundaries, and layers associated with *land use regulations* such as zoning and general plans. The layers can be different for different years, to reflect temporal changes in costs.

Physical costs include the costs of providing different levels of servicing, the cost of preparing the land before construction (depending on whether the parcel is greenfield or a brownfield) and the costs of physical changes to the building structure through demolition, renovation, addition or new construction.

Fee costs can be levied per unit of land or per unit of space, and can be one-time costs (in which case they are amortized in the same way construction costs are) or ongoing costs.

Land use regulations specify the allowed actions in Figure 4, and can also specify penalties associated with building space in areas where certain type of construction is not technically allowed (or at least not specifically encouraged) but still occurs. These penalties can represent specific real costs or fees associated with such non-conforming development, or they can represent the costs of delays or additional bureaucratic red tape. They can be represented in PECAS spatially and temporally on the basis of the quantity of space and the quantity of land in the proposed development project. The

zoning regulations also specify what level of servicing is required before a space type is permitted on a parcel, the costs of the servicing itself is a physical cost, however, and so is specified in the physical cost layers discussed above.

The GIS input layers are pre-processed into a set of database tables before SD runs.

$TrCostsS_{v,h}$  and  $TrCostsL_{v,h}$  in equation 2 are calculated from these cost layers.

### *Cost updates with construction quantities*

The probability functions described thus far are independent of any other parcel in SD. Thus SD as described so far myopically considers each parcel, with a higher probability of selecting development when development is more attractive due to higher rent or lower costs.

This is considered unrealistic due to the inelasticity of the construction industry. If many land owners wanted to develop their parcels in the same year because conditions became favorable, the construction industry would have to expand, with more overtime, imported workers, and more imports of materials. This expansion would lead to higher construction costs, which would in turn dampen demand. In fact many researchers view the development industry as the agent, searching out land owners, and allocating their limited construction resources amongst land possibilities, bidding for land in proportion to the value of Equation 2, and the landowners take into account other bids and the other non-construction options available in Figure 4 before deciding whether to accept the bid.

This elasticity of supply costs has been included in PECAS. There is a formula for specifying a quantity of annual construction capacity by space type group (typically there are two groups, *residential* and *non-residential*), and after each batch of random parcels the pace of development is compared to the specified total annual quantity. If the pace is too quick, certain construction costs are increased by a multiplier, while if the pace is too slow costs are decreased.

In this way parcels compete with each other for a limited construction budget, and the parcels in subsequent batches become dependent on the results of the simulation of parcels in prior batches.

## **PECAS Models in California**

There are five PECAS models under development in California: The Statewide Integrated Model is a model of the entire state under development for Caltrans and other state agencies for integrated policy analysis. The other models are for the four largest regional governments in California, The Sacramento Area Council of Governments (SACOG) representing the Sacramento area, the San Diego Association of Governments (SANDAG) representing the San Diego area, the Southern California Association of Governments (SCAG) representing the Los Angeles area, and the Association of Bay Area Governments (ABAG) representing the San Francisco area.

### ***The Sacramento Area (SACOG) model***

The Sacramento Area Council of Governments has a long history of integrated modeling. They provided the data required for a test bed comparison of many land use models

(Hunt, Johnston, et al. 2001). They developed a MEPLAN model and used it for policy analysis (Abraham and Hunt 1999b) (Abraham and Hunt 1999) (Rodier, Johnston and Abraham 2002) (Johnston, Gao and Clay 2005) (Clay and Johnston 2006).

The MEPLAN model was used as the starting point for PECAS model development. Extended categories of employment and households were developed, with employment categorized by industry and two occupation subgroups (white collar and blue collar) to capture management and support locations separately (Abraham, Garry and Hunt 2005). An initial model was functionally complete in 2004, but was not fully calibrated. A newer updated model was developed beginning in 2008.

### *Office vs production industry split*

Office locations of firms that also use much industrial, agricultural or retail space are commonly classified into industries based on the production at the non-office site (even though The North American Industry Classification System (NAICS) is supposed to classify *locations* based on the primary product at the location, (U.S. Census Bureau 2009) (Industry Canada 2010)). Therefore, we have to divide many industries were divided into two parts for PECAS, the “office support” part, defined as using office space and employees with white-collar occupations, and the “production” part, defined as using the relevant non-office space and the blue-collar, sales or service occupations.

### *Occupations*

The link between workers at their home and workers at their job was classified according to occupation, using Standard Occupation Classification (SOC) codes. This was to allow substitutability in the labor market based on skills and qualifications, instead of based on industry or income. The relationships between income and occupation for households, and between industry and occupation for establishments, was found to be quite strong, thus occupation was seen as an appropriate categorization for the link between households and firms in commuting flows and in the labor market. These relationships were established by the processing of the US Census’s Public Use Microsample data.

### *Luxury vs Economy Residential Space*

In PECAS there is no explicit accounting of the size of a dwelling. Activities, including households, consume quantities of space according to elastic demand functions, with the quantity and type of space shifting in response to price and other conditions, along with shifts in location by the Activities. This allows the AA module to determine the appropriate price-clearing price for each space type in each zone.

For non-residential space this tends to work well: businesses can lease more or less space in the same building, or even expand into other buildings. However it is not so easy, in reality, to consume a little more or a little less residential space – each household usually consumes only one dwelling, and dwellings do not change much in size after they are constructed.

To represent some of the inability to shift residential space, the most common dwelling type – single family dwellings – was divided into two types – “luxury single family dwellings” and “economy single family dwellings”. AA was set up so that households

could switch between the larger and smaller categories of dwelling, but SD would have to model construction events to increase the inventory of larger dwellings if many households started shifting to larger dwellings.

AA's demand functions are set up so that higher income households have a stronger preference for luxury dwellings. This provides income stickiness in home location choices in the model. For instance high income households are not likely to move into areas with smaller less luxurious housing unless the construction of improved housing also occurs. By including this feature in the model design, the combination of AA and SD can model the time-series of changing demand and resulting construction associated with the changing location preferences of different household income categories.

### *Synthetic space coverage*

The Sacramento model was one of the first to acknowledge the requirement for a synthetic built form as a starting point for urban simulation (Abraham, Weidner, et al. 2005). SACOG had a fairly extensive parcel inventory describing building type, with some information of building size. The PECAS model requires building age (to account for higher rents on brand new buildings in equation 3 and higher maintenance costs for older buildings in some alternatives in Figure 4), yet age was not available for most parcels. The categories of space in the PECAS model were chosen to reflect the industries that might occupy them as well as to reflect variation in zoning policies, fees and costs in the SD inputs. The categories of space were also expected to evolve in future iterations of model development (J. E. Abraham, G. Garry, et al. 2004). Thus the relationship between space categories in the model and space categories in the available parcel data was not one-to-one and was not expected to remain constant over model development cycles. Finally, and perhaps most importantly, the AA module represents price elastic consumption functions for space, with activities consuming less space when it is dear and more when it is cheap. Exploring the spatial relationships between employment by PECAS activity category and measured quantities of space showed that much variation in space use was due to misplaced employee data, incorrect built form data, heterogeneity within one PECAS Activity category, or large quantities of temporarily vacant space that represent market stickiness due to long lease terms.

It was decided to build a synthetic built form, containing buildings that appear realistic in type, size, age, intensity and location, but that reflect the PECAS categories of space, and at a zonal level that conform more closely to employment data which are generally more respected in regional planning than building size data. The Floorspace Synthesizer module of PECAS was constructed, which assigns a zonal level inventory of space by type to individual grid cells or parcels, using parcel attributes (such as measured built form, zoning regulations, and proximity to local-level effect features that influence rent) to guide the type of development and quantity of development on each grid cell or parcel. This allows a PECAS model to use the richness of GIS data on land coverage and land attributes while still using a simplified representation of the built-form reality appropriate for long-range policy analysis of the entire spatial economic system.



## ***The San Diego Area (SANDAG) Model***

The San Diego Association of Governments model is being constructed based on primary data from San Diego, but borrowing substantially from the ideas in Sacramento.

### *Similarities from Sacramento*

The main advances in Sacramento applied to San Diego were:

- the classification of occupation categories,
- the system for processing the PUMS data,
- the system for parcel-based microsimulation in SD,
- the split of residential space into “luxury” and “economy” designations, and
- using the Floorspace Synthesizer to establish the base-year modeled land coverage.

### *Social Accounting Matrix*

The processing of the social accounting matrix data was much improved. The social accounting matrix comes from an IMPLAN model of the region, but IMPLAN itself is designed for (aspatial) policy analysis, not specifically for reporting the relationships between different sectors of the economy. Thus aspects of IMPLAN need to be carefully extracted, and then modified for cases where the money flows in IMPLAN do not represent transport flows in the real world (Hunt, Abraham and Zhong, et al. 2005). The IMPLAN data were imported directly into a database, and the manipulations performed as database queries so that they can be reproduced as necessary.

### *Residential Space Use*

The United States Census provides an excellent resource called the Public Use Microsample (PUMS), which contains detailed individual household and person records, anonymized primarily by obscuring the location. The census asks people to describe their dwelling, but asks about the number of rooms in the dwelling, not specifically asking the floor area of the dwelling. Regressions were done with the American Housing Survey to determine a relationship between dwelling characteristics, including rooms, and dwelling size, and these regressions were applied to the PUMS data. The categories of residential space were further divided into luxury and economy designations based on the assessed value of the dwelling. The PUMS data were then analyzed to determine the relationship between household type and the size and type of housing. These data provide information to calibrate the nature of households' choice of dwelling type and size.

### *Local Level Effects*

The San Diego model was the first to operationalize the “local-level effect” rent modifiers in Equation 3. SANDAG had good data on the price of individual land parcel transactions, these were joined with distance measures and log-linear regressions were performed, with dummy variables for each LUZ, to understand the contribution of local level effects on rents. This was considered critically important in San Diego because of

the influence of the beaches on desirability and hence construction, but the local level effect modifiers estimated also included other landscape features such as schools and transportation infrastructure (freeways, major roads, major transit stops).

### *Use of space by employees*

The employment data in San Diego has been sited to individual parcels. In many cases there were more than one employment record from different industries sited on the same parcel, and in many cases there were industries associated with space types that seemed inappropriate. The real world is quite complicated and subject to measurement error. The dominant combinations of employment types and space types were identified, so that the model's representation of space use is a simplification of reality where about 80% of the employees are using the same type of space indicated by the sited employment data, and the remaining employees are allocated amongst the more dominant options.

Two different methods were used to determine the quantity of space typically used by employees in an industry. In the first case a regression was undertaken so that best-fit average space use rates were identified as a combination of a base rate for each employment industry type, and a modifier for the space type. For this regression to be successful, outliers needed to be discarded. Many outliers are extreme and consist of either one employee (in a very large building), or a vacant lot (containing many employees). The range of outliers to be excluded could be determined endogenously using formal "robust estimation techniques," but these were not employed in this case.

The second method involved tabulating the records where all the employment records on the parcel were from the same PECAS industry, and sorting them according to square feet per employee. The outliers were inspected to understand the data, and the 25<sup>th</sup> percentile and 75<sup>th</sup> percentile (of total employment in the sector) were selected to be the bounds of normal floorspace use. Many individual records outside of this bound were investigated where local individuals were familiar with the business, and Google Maps address searches, air photo inspection, and yellow-pages directory searches often strongly suggested errors in the data. The inspected records that did not seem like errors were often unique sub-industries within the PECAS industry category (e.g. some manufacturing occurs in open-air facilities with no buildings, while other manufacturing requires huge buildings to store the resulting products if those products have a high physical volume), indicating that the 32 industry categories in the SANDAG PECAS model could never fully represent the full range of space use rates observed in reality.

As a result of all this, the San Diego model has excellent targets for the typical rate of space use per employee, the range of space use, and an acceptance that the Floorspace Synthesizer will need to be run in San Diego to prepare a modeled base year built form that is somewhat different from the measured built form to account for the complexity of real-world space use and the difficulty of measuring real space quantities and employment locations.

### *Pseudoparcelling on-the-fly*

One of the reasons to use Monte Carlo simulation in SD is to avoid having to use complex statistical cross-distributions to represent the relationships between space type, intensity of development, zoning, local effects on rent, construction costs, jurisdictional

fees and age of buildings. Each unit of land has a single attribute for each of these dimensions, and the cross-relationships are evident when individual small units of land are aggregated over a LUZ or over some other geography. However some legal parcels are quite large, which would limit the ability of SD to represent complex cross-relationships. In the Sacramento model, the very large sized parcels were subdivided in the setup of PECAS (called “pre-subdividing”), but this led to a large number of individual units of land in areas of homogeneous attributes, slowing down the model runtime and adding unnecessary complexity to output presentations in areas where SD simulated no development.

In San Diego, large parcels were left as large parcels in the setup model, but the PECAS SD module itself treated large parcels with multiple samples from the Monte Carlo process, instead of only a single sample per each parcel. If any of the samples resulted in a change in the development, an appropriately small section was removed from the larger parcel, representing subdivision. Thus SD can represent complex urban form where much new development occurs on large parcels, but can also leave large homogenous parcels as single entities if no development occurs.

### ***The California Statewide Model (Caltrans)***

The California Statewide PECAS model is being developed by the University of California, Davis primarily for (and primarily funded by) the California Department of Transportation (Caltrans).

#### *Similarities from San Diego*

The main advances in San Diego that were applied to the California model were:

- the system for extracting an appropriate Social Accounting Matrix from IMPLAN,
- the categories of occupations,
- the processing of the PUMS data to determine dwelling size, dwelling type, occupation and industry, and
- the estimates of local-level effect rent modifiers.

#### *Incremental Development*

An incremental development approach was adopted for the statewide model. This provided several advantages, including 1) an opportunity to use sequential short term funding, instead of requiring a longer term multi-year funding commitment, 2) an ability to get something working with the data that is available at any time, while pursuing longer term data acquisition strategies that may require complex negotiations with many involved parties, 3) the ability to train individuals so that they can understand the entire modeling system before undertaking specific improvement projects on small pieces of the model, and 4) the ability to demonstrate success and gather support.

The milestone versions of the California PECAS model are a “setup” model in 2008, a “demonstration” model in 2009, and a “production” model to be complete in 2011.

This incremental approach had previously been successful in the Sacramento model.

### *Statewide data inconsistencies*

The fundamental challenge with the Statewide model involved dealing with the inconsistencies in data from different regions and jurisdictions. Parcel data was not available, and in underdeveloped areas of the state some parcels can be very large, thus a grid representation was used. The grid representation is a 50m x 50m grid covering the state. General plan regulations were collected from each jurisdiction, and a process of standardizing and interpreting the categories in the general plans was undertaken.

Employment data and some land cover data is available for the entire state, as are GIS feature layers useful for local-level effects. The data covering the whole state were generally used more than data that were only available for certain areas.

### *Borrowed behavioral parameters*

In initial model development, many parameters were borrowed from the estimations done in the SACOG and SANDAG development, because these agencies had invested in their GIS data quality.

### *Calibration scripts*

Some of the parameters in previous PECAS models had been adjusted manually, by comparing model output to measured reality, hypothesizing about how certain parameters impact certain outputs, and adjusting the parameters in a way that should move the outputs closer to the measured reality. Some of these strategies were familiar enough now that they could be more automated, within the practical limits of needing to be guided not only by an understanding of data quality and measurement errors, but also by an understanding of the purpose and use of the model (Abraham and Hunt 2000) (J. E. Abraham 2000). Scripts were written to run the model, compare the model output to the measured targets, and adjust the parameters. This allowed quicker calibration as the computer systems no longer had to wait for the humans to adjust the parameters before starting another model run.

### *Construction cost system and SD relational database system*

The SD software had long used various database software to store the parcels and grid cells. In the development of the Statewide model it was apparent that the database system needed to be upgraded to manage the sheer size of the state (160 million 50m x 50m grid cells) and the variation in rents, costs and fees across jurisdictions and across the variety of physical geography in California. SD was re-written to use enterprise-class relational databases, with the database software itself managing much of the internal consistency of the data. The system of calculating construction costs from GIS layers was developed.

### *Construction capacity*

The system for updating construction costs with construction quantities was implemented for the Statewide model. California is a large region with its own macro-economy; some policy scenarios regarding energy use or building standards could involve large economy-wide changes to construction costs or rents. Without a representation of the

capacity of the construction industry, SD would overpredict the changes in region-wide construction resulting from such changes in the macro economy.

### *More agriculture activity categories*

For the agriculture industry, the  $V_{e,l}$  terms in Equation 1 represent the cost of land, the accessibility of labor and other inputs, and the accessibility to output markets. The suitability of land for various agricultural uses is in the  $V_{l^a}$  terms. Test runs with the demonstration model showed that putting all of agriculture uses together in one activity category  $a$  led to difficulty in establishing the  $V_{l^a}$  terms for each zone  $l$ . Agriculture was divided into several activities based on crop groups, and other experts in the agricultural field were approached to find external models that could forecast the  $V_{l^a}$  terms and their dependence on local soil and climate conditions.

### *Fuels, electricity, recreation, water and GHG permits*

Several specific commodities were added into the production version of the California PECAS model to represent specific policy concerns. Fuels, Electricity and Greenhouse Gas Permits were added to the model, so that the choice of quantity and type of energy use could be modeled, and so that this choice could respond to changes in GHG regulations limiting the total amount of GHG production.

Water was added as a commodity to represent how many activities, including but not exclusively agriculture, choose locations where water is not scarce.

Recreation trips to parks and natural areas were added as a commodity since the household expenditure (incorporated into the model via IMPLAN) does not count the use of government-funded parks. Parks are seen to be important in the location choices of certain activities. Also, the use-based economic effects of protecting habitat areas can be directly computed in the model.

### *New travel model*

The intention initially was to integrate the statewide PECAS model with an existing travel demand forecasting model. It was found, however, that there was no suitable general statewide travel forecasting model. The most recent statewide travel demand model developed was the High Speed Rail model, but it was focused on forecasting the demand for trips on High Speed Rail, and as a result was not suitably responsive in certain regions or for certain types of trips. A separate project was begun to develop a new travel demand model for California, for general use and to integrate with PECAS for integrated land-use and transport policy analysis.

### *Training and staff development*

The California PECAS model is a large project undertaken by a partnership between a consulting firm, a university, and an agency. This forced a more formal approach to project management. The steps involved in building a PECAS model were described as a series of 38 separate functional tasks, some involving subtasks. These tasks helped with

staff allocation, and also enabled more junior staff to understand how their own work fit into the larger model development effort.

The project is also designed to develop skills in people for the longer-term, when this type of modeling is more widespread and has a larger influence on policy decisions. The University of California, Davis, is undertaking to educate agency staff, students and post-doctoral fellows, and a portion of the effort in developing and documenting the model has this larger goal in mind.

### ***The Los Angeles Area Model (SCAG)***

The Los Angeles region PECAS model is being developed by the Southern California Association of Governments (SCAG). SCAG had been planning their model development for some time, with design iterations and discussions going as far back as 2009.

#### *Similarities from California Statewide*

The main advances in California that were applied to the Los Angeles model were:

- the categories of employment activities, household activities, goods commodities, services commodities and space,
- SD GIS and input database system, and
- scripts for repeated runs during calibration.

#### *Parcels*

The Los Angeles model uses a separate more detailed cadastral data set, adding detail to the grid cell data inherited from the statewide effort. (This parcel data has been fed back to the Statewide model effort, to further inform future grid-cell representations of the Los Angeles area in the statewide model.)

#### *Spatial Database*

The new SD database structure developed for the statewide model was integrated with a spatial database extension in Los Angeles. This allows model outputs to be queried directly by GIS software, without intermediate preparation steps. In Los Angeles more automated systems of output map presentations are being explored; for instance web mapping technologies would allow immediate viewing of model results in a web browser.

### ***The San Francisco Area Model (ABAG)***

The San Francisco region PECAS model is being developed by the Association of Bay Area Governments (ABAG). ABAG is starting with the statewide model, trimming out the region and a surrounding “halo” area around the region. The project has just begun.

#### *Planned similarities from California Statewide*

Most of the features of the California model are planned to be included in the San Francisco model, including:

- Activity and Commodity categories
- Social accounting matrix coefficients, except for labor where more refined regional numbers from PUMS will be used
- SD GIS and input database

### *Halo region*

The region is legally required to analyze the impact of people commuting to the region, and in particular the situation where construction of buildings occurs outside of the region with much commuting into the region. Thus, there needs to be a model of residential construction for areas well outside of the regional boundaries. The current plan is simply to extend the model boundary further out, to include a halo of area around the region and hence cover the full range of commuting possibilities to the region. However there are two identified problems with this, 1) the transportation model (TR in Figure 1) is not expected to cover the halo region, leading to complexity in establishing transport disutilities required between all zone pairs, and 2) the land cover data available to the region does not cover the halo, leading to inconsistencies in both SD and the Floorspace Synthesizer across the regional boundary.

An alternative plan is to only cover the region with the PECAS model, but have a separate model of in commuting that takes into account construction costs and possibilities for housing in the area surrounding the region.

### *Zoning*

One of the policy variables to be analyzed by the ABAG model concerns the different zoning permissions in different jurisdictions. In the statewide model, it was essential to simplify and interpret the general plan categories to ensure a consistent treatment for the entire state of California. For the ABAG model the intention is to add some detail back into the zoning information for PECAS – still keeping the simplified zoning regulation types that were established for the statewide model, but interpreting them slightly differently in the different jurisdictions that make up the San Francisco Bay Area.

## **Resources required in the development of the PECAS models in California**

### ***Data***

The PECAS model is conceptually simple: fundamentally it consists of equation 1 representing location, technology and exchange choices in AA, and a number of equations very much like equation 2 representing the attractiveness of the various development options shown in Figure 4. Yet building such a model to represent the entire spatial economic system is a large undertaking requiring quite a bit of data.

### *Geographical (GIS) data*

Geographical data is required in many forms. Complete data is not required for all elements, as the behavioural system within PECAS forces some consistency in land use. Typical elements are shown in Table 1.

<b>Physical Geography</b>	<b>Local-level effects (sub LUZ rent modifiers)</b>	<b>Land use regulations</b>	<b>Activity locations</b>	<b>Built form</b>
Slope	Exact school locations	Development impact fees	Employment by industry/occupation	Locations of buildings
Service costs	Coast/Beach	Permitted uses (both permitted and discretionary/acknowledged)	Households and population by household categories	Size of buildings
Natural endowments for production (soil, climate, presence of minerals)	Freeway, freeway ramps	Servicing requirements	Wages and occupations	Age of buildings
	Major roads		Prices for goods and services	Type of buildings
			Zonal attractors (crime rates, school quality, etc.)	Location of construction

Table 1: Typical spatial data elements

### *Choice data*

Choice data describes the choices made by the agents in the simulation, and is used to understand what influences choices and the how choices are likely to change under future conditions. In most cases disaggregate data describing individual choices are most valuable, as it allows a greater understanding of the way conditions influence choices. Typical elements of choice data required are shown in Table 2.

<b>Household choices</b>	<b>Business/ Institution choices</b>	<b>Developer choices</b>	<b>Choices made by (or interacting with) the “rest of the world”</b>	<b>Landlord choices</b>
Commuting distances or flow matrices, and travel conditions	Shipping distances or flow matrices for goods, and travel conditions including	Size and intensity (size/land) of buildings constructed (spatial)	Growth rate for the economy, by category	Vacancy rates under different conditions



	shipping costs			
Distances or flow matrices for consumption trips (shopping, education, personal services, etc.), and travel conditions	Service trip distance or flow matrices, and travel conditions	Cost of construction for new buildings (spatial)	Directionality, quantity, and elasticity of imports and exports for goods, services and labor.	
Investment decisions	Leases signed, amount of space and number of employees	Cost of maintaining older buildings.	Growth rate for population, by household category	
Occupation by household type, and wages earned by location	Occupation of employees for each employment establishment, and wages paid by location		Changes in productivity/production functions	
Size and type of dwelling	Production function			
Household Expenditures	Government expenditure on health and education			
Value of home (rent value)	Location of major government planned facilities including colleges, parks, military bases			

Table 2: Typical choice data elements

### ***Travel Model***

The development of the California PECAS models all relied on the presence of an existing general purpose travel model. In the case of the four regional models, these provide the travel conditions over time in the integrated sequence of simulation shown in Figure 1. In the case of the Statewide model, the most recent existing travel model was not general purpose enough to integrate with PECAS, but it served as the foundation for the concurrent development of a new travel model.

## Staff

The development of an integrated land-use and transport policy analysis model requires substantial human resources. It is critical that the staff in the agency responsible for policy analysis be involved in the model development. A consulting firm familiar with the development of such models seems necessary to provide overall guidance, to undertake some of the more involved production work in data analysis and preparation, and to provide software development skills. University involvement can lead to the development of new individuals at the graduate student level, facilitate training of agency staff, and can organize more exploratory research into future techniques.

Within these organizations, numerous skills are required. Some of these are listed in Table 3, with columns indicating possible position names. Within each column a “d” indicates a desirable skill for the position, whereas an “e” represents an essential skill for the position.

Function	Land Use Modeller	Transport Modeller	Computer Programmer	Computer Systems Administrator	Office Administrator	Project Manager	Data Intern	Supervisor
Software programming								
- SQL scripts			e	d				
- Java			e					
- Python (scripting)		e	e	d				
- GIS programming			e					
- Software guide/ programmers reference guide			e					
User guide	d	d	d					
GIS analyst (skill most everyone needs to be trained in)	e	e						
Software architecture/design	d	d	d					
System Administration (Version control, hardware purchase, software install and upgrade)				e				
Statistical Estimation (Maximum likelihood)	e	e						
Model calibration (e.g. logit model constants and dispersion parameters)	e	e						d
Model operation	d	d	d					
Writing the model operations manual	d	d	d					
Data finding (BTS, Census, Elevator permits, BLS, ES202, InfoUSA, Tax	e							

Assessor, Parcels etc.)								
Data synthesis	d	d						
Data work (e.g. reformatting/entry)								e
Data work supervision								e
Process and data documentation	d	d	d					e
Theoretical Mathematics	d	d						
Model's underlying theory	e	E	d					
Project Management (contracting, flow, resource allocation)								e
Client Liaison								e
Project administration (timesheet, expense, phone, office space, supplies)								e
Preparation of presentation materials	d	d						e
Academic paper preparation	d	d						e
Economic supply/demand analysis (CGE Modelling, IO Modelling)	e							
Regional economic forecasting (IMPLAN, REMI, County Business Patterns, Structural Equations)	e							
Urban Economics	e							
Transport Modelling (Assignment software, Transport Network Analysis, Screenlines, Fratar)								e
Developing course materials								d
Managing course delivery (administration)								d
Delivering training and courses	d	d						
Recruiting staff and students	d	d	d	d	d	e	d	d
Mentoring students	e	e						e
Legal/Contractual								d

Table 3: Skills in model development and possible position names

## Conclusions

The PECAS models in California are being developed on an ongoing and incremental basis, with each succeeding model benefiting from the work in the previous model. The models are being developed incrementally, so that model development can continue while earlier versions are being tested on broad policy analysis work. This also allows the earlier adopters to benefit from others' experiences with operating models when they undertake model improvements.

The agencies have been cooperating with each other. One of the advantages of the regional government system is that each agency has a clearly defined jurisdiction, thus they do not feel that they are in competition with each other, as might occur in the case of a good or service provided by unregulated private companies. Each feels that they will benefit if their neighbors are also able to undertake a better planning process through better modeling. This, combined with the open-source license for the software itself, has led to cost savings in software development.

The five models all use the same theoretical structure and software, with changes in the definitions of categories (Activities, Commodities, Zones, Space types, Zoning). This allows skills, knowledge and even parameters to be shared across the agencies. The SCAG, ABAG and the “demonstration” version of the Statewide model even share most of the same categories.

The modeling framework has shown itself to be a practical policy analysis tool. Various test scenarios have been evaluated, mostly for internal consumption within the agencies. Although this paper is not about model application, it is worth noting one important study (Rodier, et al. 2010) where the AA module for Sacramento was able to show that more compact future growth plans would benefit lower income households more than higher income households.

These models are quite complex, and can be quite expensive. It is important to not get too ambitious in model design, especially if budgets are limited. It has been found useful to visualize a complex and comprehensive model design, but then to build an initial version that is simpler. This allows such models to be used and run in sequential model builds. As the models encompass the entire spatial-economic system, inevitably many aspects need to be quite simplified to fit into the consistent representation system. Some simplifications are easier to accept if they are viewed as temporary compromises, adapted only to get the current iteration of the model running. Additional complexity can be added in the future if the initial simplified representation turns out to be inadequate.

These models are policy analysis models. Whether a simplified representation is adequate or not depends largely on the policies to be analyzed. The modeling system is quite flexible; most representations of spatial behaviour can be adapted to equations 1 or 2 given appropriate categorization systems for activities, technology, commodities, space or land. Adding more detail in the representation of certain things usually involves adding categories; for instance the analysis of greenhouse gas emissions in the “production” version of the statewide model involved adding fuel, electricity, and greenhouse gas permits as commodity categories.

It is expected that future research will show in more detail the policy analysis capabilities of the models. In particular it is hoped that a set of comprehensive models covering the state and its major regions will improve regional and state decision making on land use, transportation, and greenhouse gas planning, and that future work will be able to measure this improvement.

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