The Journal of Transport and Land Use http://jtlu.org
Vol. 12 No. 1 [2019] pp. 443–474

Building a PECAS Activity Allocation Module: The experience from Caracas

Geraldine Fuenmayor
HBA Specto Incorporated
gfm@hbaspecto.com

John E. Abraham
HBA Specto Incorporated
jea@hbaspecto.com

John Douglas Hunt
University of Calgary
jdhunt@ucalgary.ca

Abstract: We applied the PECAS Framework, a spatial economic system for forecasting and policy analysis, to the region of Caracas, Venezuela. In this paper, we describe in 12 steps the elements developed for an Activity Allocation model in this region. A detailed inventory of built space and household characteristics was developed using a population synthesis technique. The model design and implementation reflected informal (slum) housing and social equity (with 20 residential space types), while accounting for the industrial mix of the region. Transport costs for economic interactions were calculated using a TRANUS travel demand model. We also describe the calibration of the model and the application to two policy scenarios: provision of public housing and increasing transit fares. The 12 steps can guide future researchers, specifically listing the data and processes that were applied in this context. The sensitivity tests showed how this type of model can be used to anticipate social equity effects due to policy. Based on the know-how gained, we provide valuable insights for other modelling teams, particularly for applications in developing economies.

Article history:
Received: March 31, 2017
Received in revised form:
May 3, 2018
Accepted: April 9, 2019
Available online: June 14, 2019

1 Introduction

A spatial economic model of the Caracas Region in Venezuela has been developed using the PECAS Framework (Fuenmayor, 2016). It is called "PECAS Caracas." It provides a simulation of the location, technology and exchange decisions of households, businesses and public agencies in response to (a) endogenously-generated rents for space and prices for inputs and outputs and (b) accessibilities to these inputs and outputs arising from their spatial distributions and the generalized costs due to travel between them. It uses the PECAS Activity Allocation (AA) Module, considering the short-run where building space is fixed regarding type, quantity and spatial distribution. The evolution of the supply of space over time, from one time period to the next, covered by the PECAS Space Development (SD) Module, is not included; the intention was to add it in a subsequent version of PECAS Caracas.

The work done to build PECAS Caracas was substantial, had to overcome big challenges, included dead ends and provided opportunities that were recognized and sometimes taken. The experience taught lessons and provided useful and practical appreciation and know-how, which has potential value to those undertaking this sort of model development in varied contexts.

http://dx.doi.org/10.5198/jtlu.2019.1188
ISSN: 1938-7849

The *Journal of Transport and Land Use* is the official journal of the World Society for Transport and Land Use (WSTLUR) and is published and sponsored by the University of Minnesota Center for Transportation Studies.

More specifically, population synthesis techniques were used to extend and harmonize detailed inventories of households, employment and built space starting from the complete national census database and several forms of remote sensing data. The model design evolved to include 20 residential space categories, reflecting the quantity and range of formal and informal (slum) housing types and their role in social equity considerations. The model was linked with a modified form of an existing TRANUS transportation system model. A specific step-by-step process was developed and partly automated for performing the iterative "enhancement and recalibration" tasks central to the agile approach used in model development.

Most PECAS modelling to date has concerned cities and regions in developed countries, particularly in North America. This is changing with ongoing efforts in China and South Asia. But Caracas was the first region in South America to be considered with PECAS, and it presented novel issues and challenges requiring novel solutions.

This paper describes the work done to build PECAS Caracas and presents key lessons learned and components of practical experience and know-how gained. In one sense it is like the annals of an expedition into unknown territory: it provides a record of how this effort to build a model in a new context was completed successfully and what was encountered along the way. In another sense it is like a travel guide that identifies what should and should not be missed by a new arrival based on the experiences of those going before: it shares hard-earned insight and guidance that will help make the efforts of others more effective.

2 The Caracas region

Caracas, the capital of Venezuela, is the major city in the Caracas Region, an urban area of around 5 million people located in the north of South America (Figure 1).

The national economy is dominated by oil and gas exports, but Caracas's economy is focused towards the production of services (Figure 2). However, oil production in Venezuela is the main source of income to support government expenses. In the last 40 years oil revenue reached a peak in 2008 and had a second period of high revenue between 2011 and 2013. Inflation rates were high, but less than 100% until 2014. After 2014 they became unreasonably high, around 500% for 2017 (Figure 3) and more than 1,000,000% for 2018 (Trading Economics, n.d.). This high inflationary context (Banco Central de Venezuela, 2007) encouraged households to buy properties, or construct their own homes in slum areas, rather than renting, to preserve capital. Besides this hyperinflation, the decrease of oil production and crude exports led to a big socioeconomic impact that included food shortages, a health crisis, an increasing murder rate, and a massive exodus of population mainly after 2015 (National Bank of Canada, 2018).

Caracas, like cities in many developing countries, has grown through both formal land development and informal, unregulated development, also known as slums (Figure 4). The floor space built in the slum areas is about 35% of the residential space in the Region (Fuenmayor, 2016).

Caracas is a dense city, where most of the buildings in the main valley have more than 20 stories and about 30% of the population live in apartments (Fuenmayor, 2016).

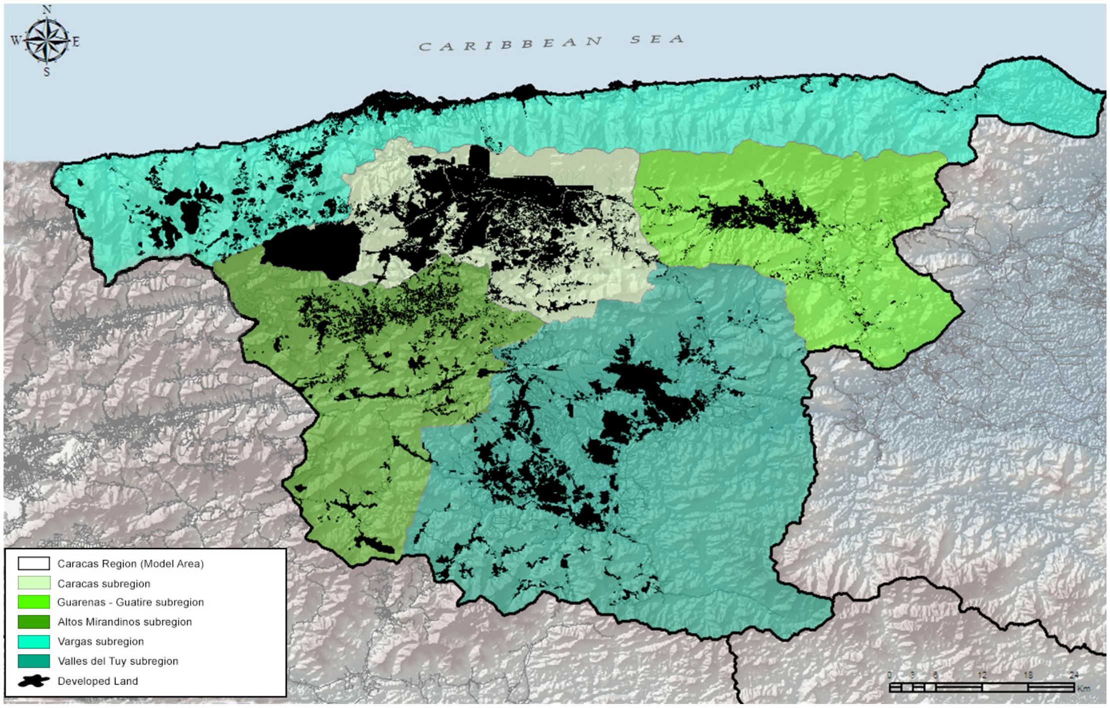


Figure 1. Five subregions defined in the Caracas region

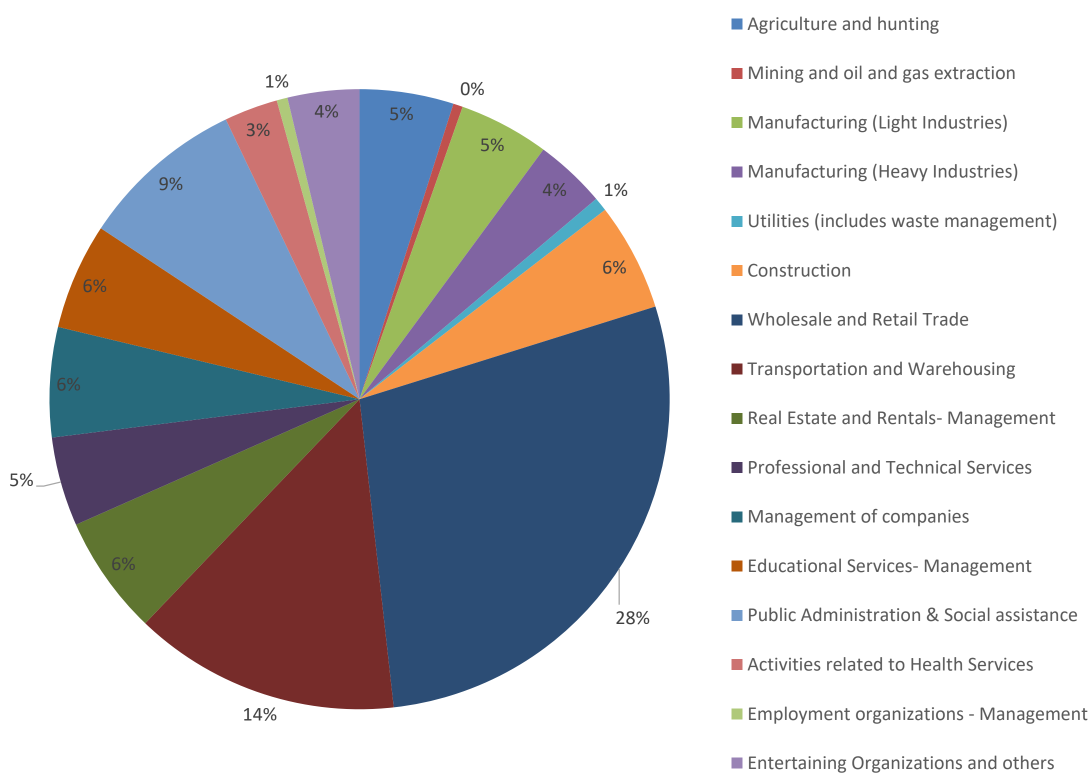


Figure 2. Distribution of the employment by industry for the Caracas region

Source: Proportions based on 1997 economic production Government site. Matriz Insumo Producto Año 1997. http://www.bcv.org.ve/cuadros/series/mip97/mip97.asp?id=425 by Banco Central de Venezuela

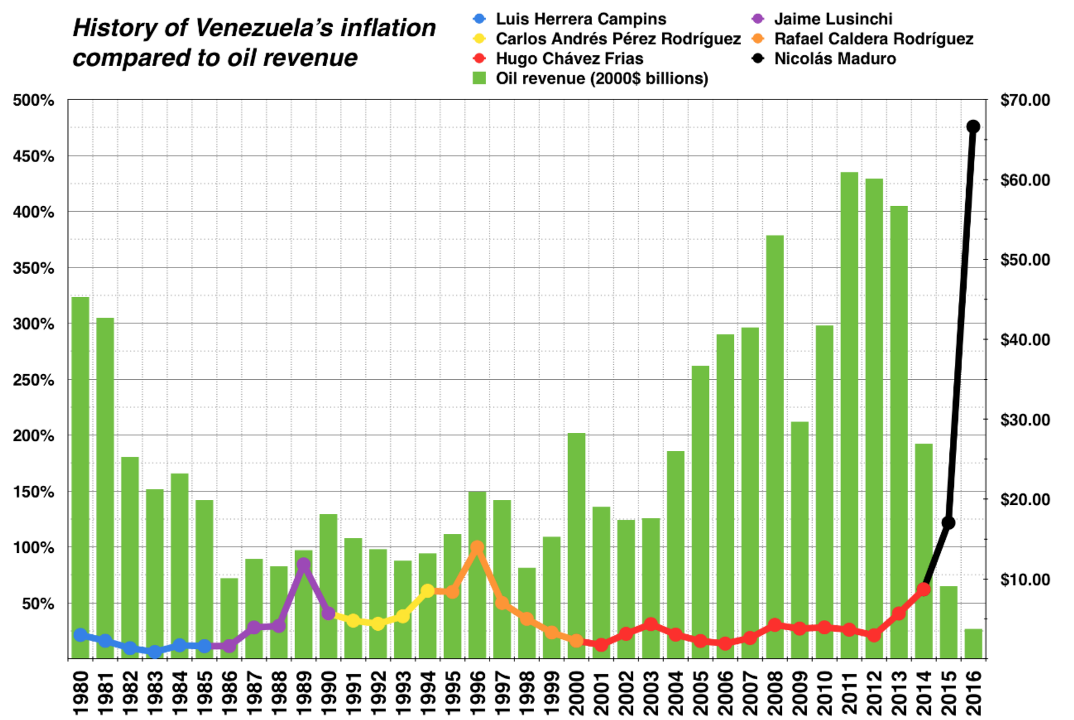


Figure 3. Venezuela's historic inflation rate beside annual oil revenues

Sources: EIA 1, EIA 2, International Monetary Fund: Data & Statistics (1980–2008; 2015), CIA: The World Factbook (2009–2014), Business Insider (2014, 2015). Taken from the page https://commons.wikimedia.org/wiki/File:Venezuela_historic_inflation_vs._oil_revenue.png

In the Caracas subregion, 59% of personal travel is by public transit, 23% by foot and 18% by automobile (Modelistica, 2005).

Figure 4. Slums and multifamily in the Caracas region

3 PECAS modelling framework

PECAS (Production Exchange Consumption Allocation System) is a generalized approach for simulating land use within integrated land use-transport models (Hunt & Abraham, 2005), for policy tests and forecasting.

3.1 System of modules in PECAS

A full PECAS model has four modular components (Hunt & Abraham, 2009), run in a year-by-year simulation (Figure 5).

- The AA module performs a short-term (1 year) equilibrium allocation to zones and flows in each year of the simulation up to the planning horizon.
- The SD module represents developer behavior in evolving built form.
- A Transportation Demand module (TR) takes the locations from AA and determines the performance of the transportation system and the resulting zone-to-zone travel utilities.
- An Economic and Demographic model (ED) represents the interaction of the region with the national and international economy

Each activity (category of business or household) produces and sells puts (inputs and outputs). Categories of puts include goods, services, labor, and space. The relationships between the inputs bought and consumed by an activity and the outputs produced by it define its possible production technologies.

The activities, as the actors in the AA module, make three allocation choices: where to locate, what technology to use, and where to buy inputs and sell outputs. These are represented according to random utility theory (Abraham & Hunt, 2007), with the following utility function with different parameter values for each category of activity (Hunt & Abraham, 2005):

$$U_{lpe_1e_2\ldots e_n} = V_l + \varepsilon_l + V_p + \varepsilon_{lp} + \sum_{n=1\cdots N} \left|\alpha_{pn}\right| s_{pn} \left(V_{e_nlp} + \varepsilon_{e_nlp}\right) \qquad (1)$$

where:

l = the location of the activity

V_l = the measurable component of utility associated with the location l and activity a

ε_l = a random component of utility associated with location l and activity a

Vp = the measurable component of utility associated with the technology option p

ε_{lp} = a random component of utility associated with the technology option p and location l

α_{pn} = the technical coefficients associated with technology option p, representing the quantity of a put produced (if positive) or consumed (if negative)

s_{pn} = a scaling factor associated with the technical coefficient α_{pn} (non-negative and usually 1.0)

Ve_nl = the measurable component of the utility of exchanging the put associated with αpn in exchange location e_n, given location l and technology option p, including the price utility (positive if selling, negative if buying) and the transport disutility.

εe_nlp = a random component of utility associated with exchanging the put at exchange location e_n, given activity location l and technology option p, which after integration leads to the size component of utility.

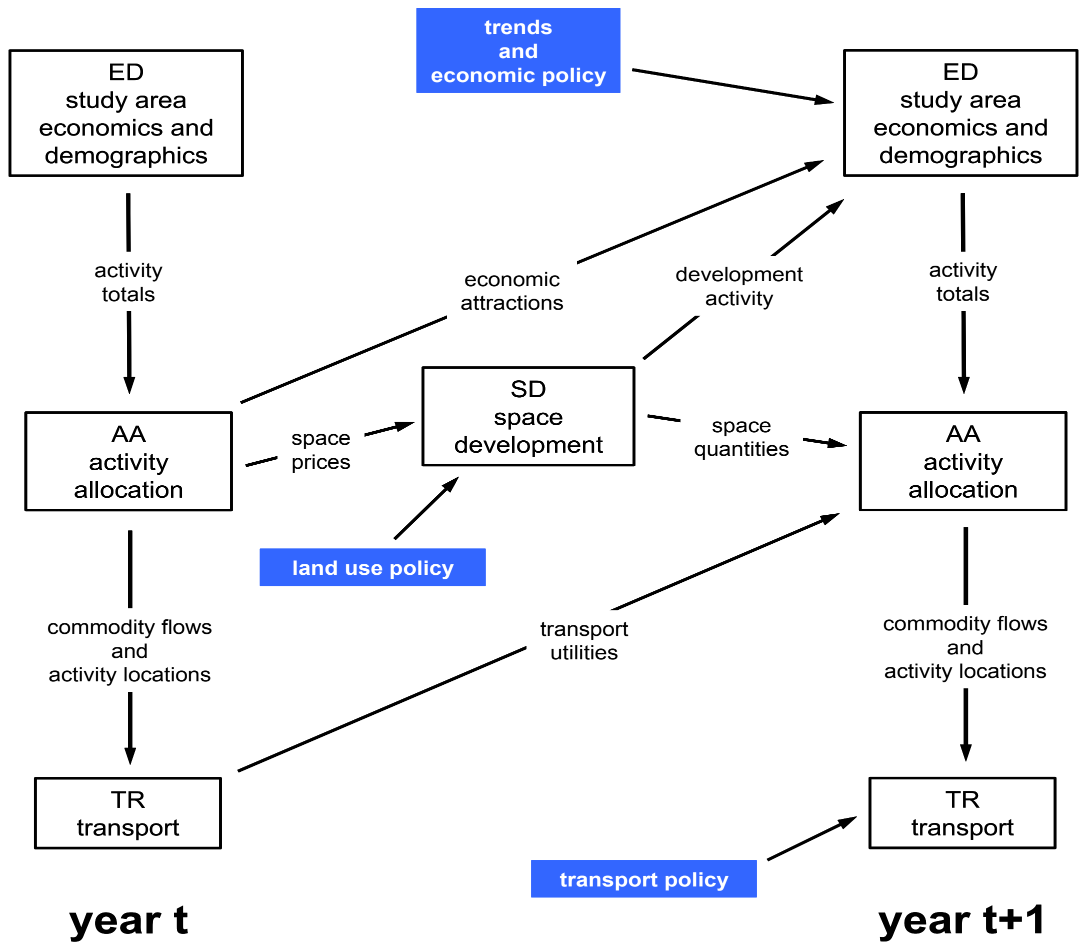


Figure 5. Modules and information flows simulating temporal dynamics

Source: PECAS – for Spatial Economic Modelling. Theoretical Formulation by Hunt and Abraham (2009)

4 Elements of a PECAS Activity Allocation module

Different elements are required to develop an AA module. The general requirements for PECAS are summarized in Table 1.

Table 1. Model elements required to build an Activity Allocation module of PECAS

Elements of the model	Description
1. Zone system	Locations in AA are represented using a system of zones, called Land-Use Zones (LUZs), each consisting of one or more of the Transport Analysis Zones (TAZs) used in the Transport Demand Model TR.
2. Activity definitions	Economic activities are represented in categories of five types: Households, Firms, Non-profits, Government and Factor Accounts. Households are normally categorized by size and income. Firms (industries) are categorized based on outputs, technology, and associated input requirements.

3. Put definition	The Inputs and Outputs of economic activities are of five types: Goods, Services, Labor, Space and Finance/Capital. These are distinguished by physical form, divisibility, unit value and transportation cost. Market clearing prices are determined for each put in each zone. Goods include raw materials, intermediate products, and manufactured goods. Services include education, health, professional and technical services, wholesale, retail, management, financial services, insurance, and real estate. Labor is categorized by occupation: managers, medical workers, teachers, sales representatives, drivers, farmers, etc. Space is categorized into several types of residential and non-residential buildings, as well as other land improvements. The put categorization depends on the scope of the project, the availability of data and the objective of the modelling work.
4. Design Diagram	The relationships between activities and puts, as well as their functional form, is documented in a standard format called the PECAS Design Diagram. For example, the Design Diagram could indicate that the production and consumption of goods and services by industries and households occurs at a fixed rate, while the production of labor by households occurs at an elastic rate to endogenously represent labor force participation and unemployment.
5. Aggregate Economic Flows of puts among activities	The model-wide levels of economic interaction in the full model area are called the Aggregate Economic Flows of puts between activities. These establish the average rates of production and consumption by each activity category. For activities that are firms, this is the average production technology for the category. For activities that are households, this is the rates at which goods, services and space are consumed, and labor is produced — in essence the average 'lifestyle' for the category. For government and factors accounts these can include region-wide spending allocation, such as government spending on health and education. In an urban planning context, the focus is on six main relationships between activities and puts: • Firms consuming and producing goods and services • Households consuming goods and services • Firms consuming (hiring) labor occupations • Households producing labor by occupation • Firms consuming non-residential space • Households consuming (living in) residential space The PECAS Aggregate Economic Flow Table (AEFT) has a layout that follows the PECAS Design Diagram.

6. Floor space by zone (built form)	Floor space is a special category of put; it is a fixed capital asset required as an input for many activities. It is non-transportable in that it must be exchanged and consumed where it was previously produced or constructed. It provides much of the fixedness and inertia in the locations of activities over time. Its production is simulated in the SD Module and provided as an input to the AA Module. A representation of the quantities of floor space by type and zone for one or more years is developed as an input to AA. The primary direct measurement is often the cadastre from the legal ownership records or property tax assessments, but remote sensing data (imagery, terrain elevation, LIDAR, etc.), population information, vacancy rates, employment summaries, market summaries including rental rates, and other sources are usually used to supplement the cadastre.
7. Spatial distribution of activities	The locations of activities are represented as quantities in zones. These values for one or more years are used as targets in model calibration. These targets are often synthesized from proxy variables and less than complete observations. The work involved in their development can be extensive.
8. Flows of puts	The flows of puts from the location and activity of production, through the exchange location, to the location and activity of consumption are synthesized in the model as flows between zones. Quantifications of the corresponding flows in the real world are used as targets in model calibration. In principle, these could be full origin-destination matrices developed by observations or synthesis, but in practice only the distributions of trip lengths are typically used.
9. Imports and exports	Imports and exports are treated as money interactions crossing the boundary of the region, including domestic and international imports and exports, with associated transport costs and elasticities.
10. Transport costs	The flows of exchanges from production (selling) zones to exchange zones and from exchange zones to consumption (buying) zones are allocated using multinomial logit models. The cost of transporting a unit of each put is based on zone to zone measures of transport attributes from a transportation model (e.g., matrices of travel time, travel distances and/or composite cost from a mode and route choice model). Observations of transport costs or perceived disutility are required to establish each put's transport cost coefficients, which transform transportation model units (e.g., cost per journey) to economic units (e.g., shipping cost per dollar of product).
11. Observed prices by zone	The AA module requires observed prices of puts in different locations. If the model covers a very large region, observations of prices for many puts may be available. For example, consumer price indices and labor market indices may be available for individual cities within a province or state. In all models, regardless of scale, observations of rent by space type and zone are required as targets for calibration.

12. Short-term floor space supply functions	The short-term floor space supply functions dictate the landlord's willingness to accept rent for space when demand decreases for any space type. Floor space supply curves need to be extrapolated beyond observations, so that PECAS can represent extreme situations (e.g., 100% local vacancy) during the numerical search procedure and provide model results in extreme policy scenarios. These are based on rent data and occupancy rates of housing and non-residential space types, often collected in a census or provided by the real estate industry. The central part of the curve is matched to observations, while the extreme ends (very high prices, very high vacancy rates) are based on theory and expert opinion.
13. Observations of technology choice	The elasticity in the rates of production and consumption by each activity category are represented in AA as a choice between discrete options. The set of alternatives is developed based on observations of differential production and consumption, in particular for labor and space. The same observations are used as calibration targets so that the base scenario represents the choices made under the observed conditions.

5 Model steps and elements to build an Activity Allocation module for Caracas

The previous section described the functional elements of data, observations, and accomplishments that need to be developed for a PECAS AA module. But these elements are connected and interdependent, and in our experience, some are developed in parallel, while others are developed in sequence, with iterations of improvements as the model emerges from the work to build it, like a sculpture emerging from the marble. In this section, we present the work done to build the AA model for Caracas as 12 steps, with the steps described in Figure 6. Table 2 shows how each step accomplished partial of full versions of each element, and how some elements were used to support the later steps.

Step 0. Defining a zone system

The *zone system*, element 1 in Table 2, was taken from a previous land-use modelling work for the Metro Company in Caracas, finalized in 2007 by Insurbeca. Other critical data was also available from this study, so 2007 was also chosen as the base year for the model.

Step 1. Estimating built form

The built form is an inventory of the quantities of floor space by type and by zone, including residential and non-residential space.

Initially, a building footprint layer (Insurbeca, 2007) was overlaid with land-use polygons to obtain a land-use category for each building. Then, the number of floors for each building was established by subtracting the elevation of the roof plan from a terrain elevation layer (Martinez, 2007), with manual corrections using satellite images.

Figure 6. Activity Allocation module development process in 12 steps

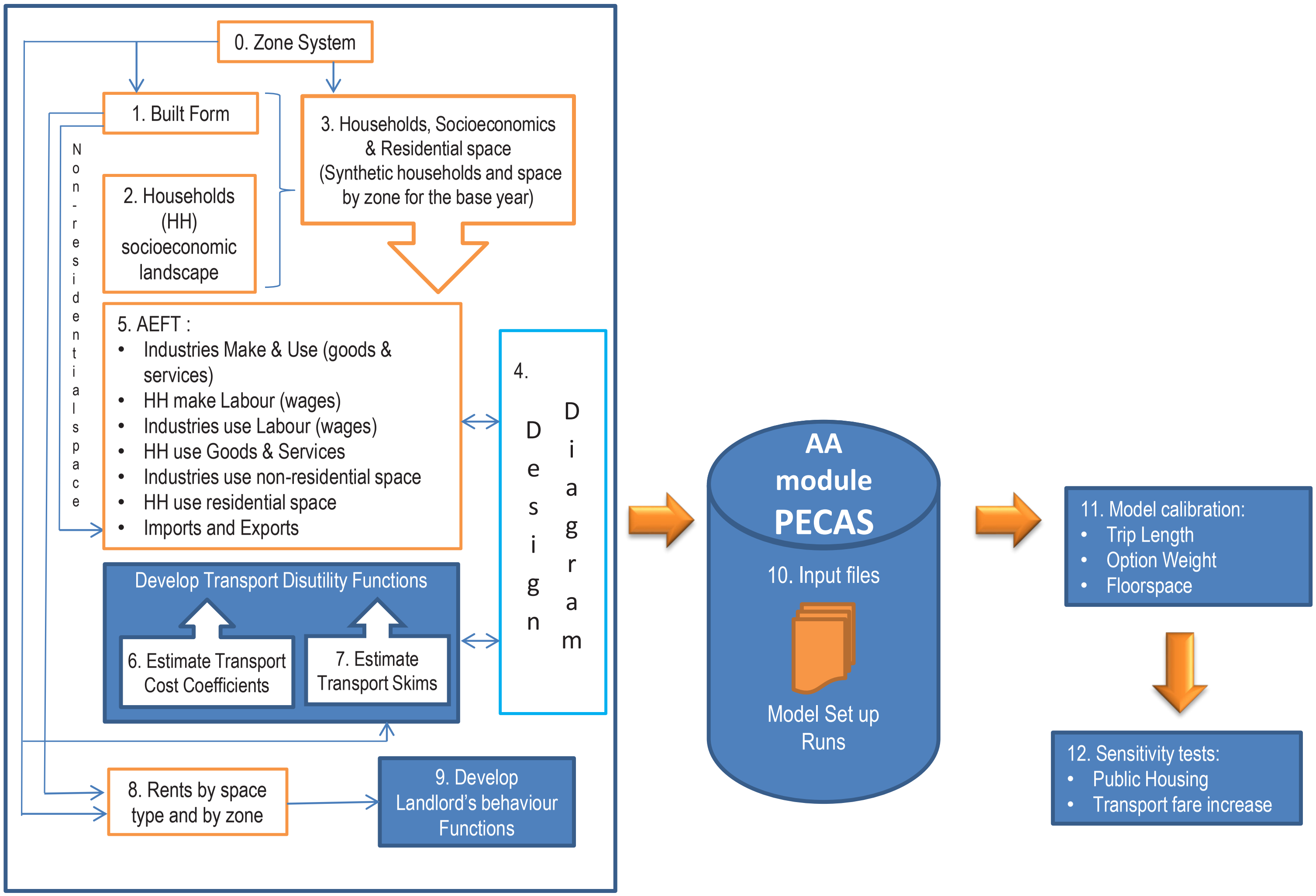


Table 2. Elements developed and used by steps in the AA module of Caracas

Steps versus Elements	1. Zone System	2. Activity definitions	3. Puts definitions	4. Design Diagram	5. Aggregate Economic Flows	6. Floor space by zone (Built Form)	7. Spatial distribution of activities	8. Flows of puts	9. Imports and Exports	10. Transport Costs	11. Observed Prices by Zone	12. Short-term floor space supply functions	13. Observations of technology choice
Step 0. Defining a zone system	●												
Step 1. Estimating Built Form	■		○			○							
Step 2. Defining the socioeconomic landscape of households		○											
Step 3. Generating synthetic households and, residential and non-residential space use rates		●	○			●	●						●
Step 4. Completing the Design Diagram		●	●	●		●							
Step 5. Developing the Aggregate Economic Flow Table (AEFT)		■	■	■	●	■			●				
Step 6. Estimating the Transport Cost Coefficients			■		■					●			
Step 7. Generating transport skims for Caracas	■							○					
Step 8. Estimating rents by space type	■		■								●		
Step 9. Landlord behavior functions by space type			■								■	●	
Step 10. Running the AA module					■	■	■		■	■		■	
Step 11. Calibrating the model								●			■		■
Step 12. Performing sensitivity tests					■	■	■	■	■	■		■	■

Legend: Element Partially developed ○ Element fully developed ● Element used after development ■

The resulting calculation of space by type and by zone was compared to the count of housing units by type from the census, using dwelling size as measure for validation. Outliers were investigated and adjusted using satellite images. These revisions were a time-consuming process when discrepancies were found, but the resulting residential space inventory by zone was reliable and consistent. Later, the space inventory was used as targets by zone for the synthesis of households and for the calculation of the residential use rates. The amounts of space were also aggregated in the AEFT (Step 5) to determine space use rates. An overview of the floor space by zone is shown in (Figure 7).

Two elements were partially developed in Step 1: *Put definitions and Built form* (Table 2).

Step 2. Defining the socioeconomic landscape of households

Reported income values are not reliable in Venezuela, so a socioeconomic categorization system for households was developed based on poverty: out of poverty, in poverty, and in extreme poverty. This is based on a point system based on six household attributes: dwelling unit type, people per washroom, number of vehicles, education level, postgraduate education, and type of LUZ and floor space quality by subregion (Fuenmayor, 2016).

Points are associated with ranges of each of the six attributes, and the socioeconomic level is based on the number of points assigned. The break points for the proportion of each type were obtained from the 2005 Travel Survey performed by Modelistica. The number of households by category is shown in Table 3.

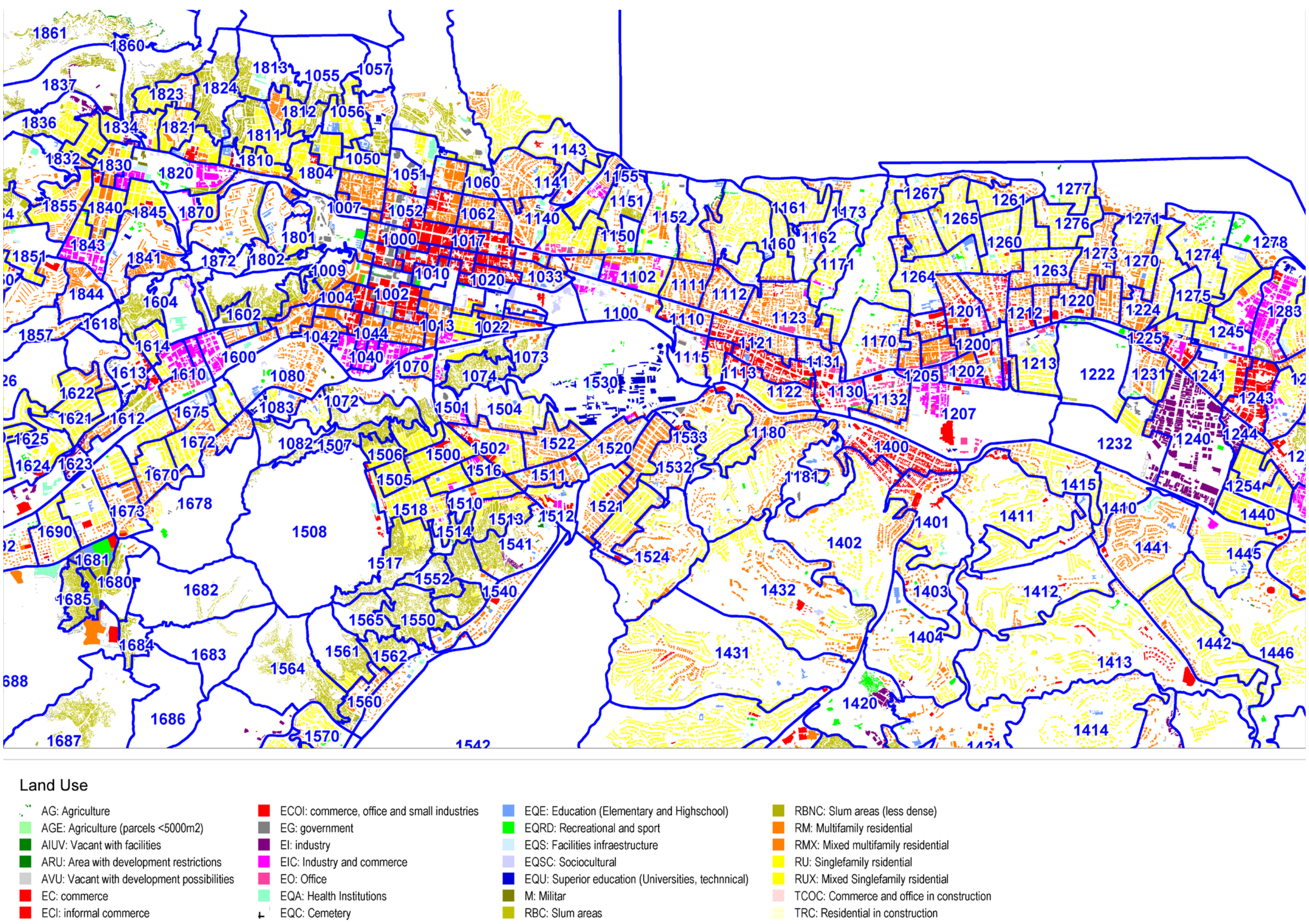


Figure 7. Partial view of space type by building by zone

For the type of LUZ and floor space quality by subregion, a categorization was developed in parallel with the floor space estimation (Step 1) and rent estimation (Step 8), by considering the quality of the construction, land prices, and densities of construction by zone. LUZs having similar price-density relationships were considered to belong to the same markets. These relationships for single family units show higher prices in the Caracas subregion (Figure 8).

Only one element was partially developed in Step 2: *Activity definitions* (Table 2).

Table 3. Household categories

Household category	Number of Household	%
1 to 2 people out poverty (level abc)	111,116	8%
3 to 4 people out poverty (level abc)	220,209	15%
5 people & plus out poverty (level abc)	112,270	8%
1 to 2 people poverty (level d)	176,830	12%
3 to 4 people poverty (level d)	230,957	16%
5 people & plus poverty (d)	119,251	8%
1 to 2 people extreme poverty (e)	43,441	3%
3 to 4 people extreme poverty (e)	171,326	12%
5 people & plus extreme poverty (e)	259,820	18%
Totals	1,445,220	100%

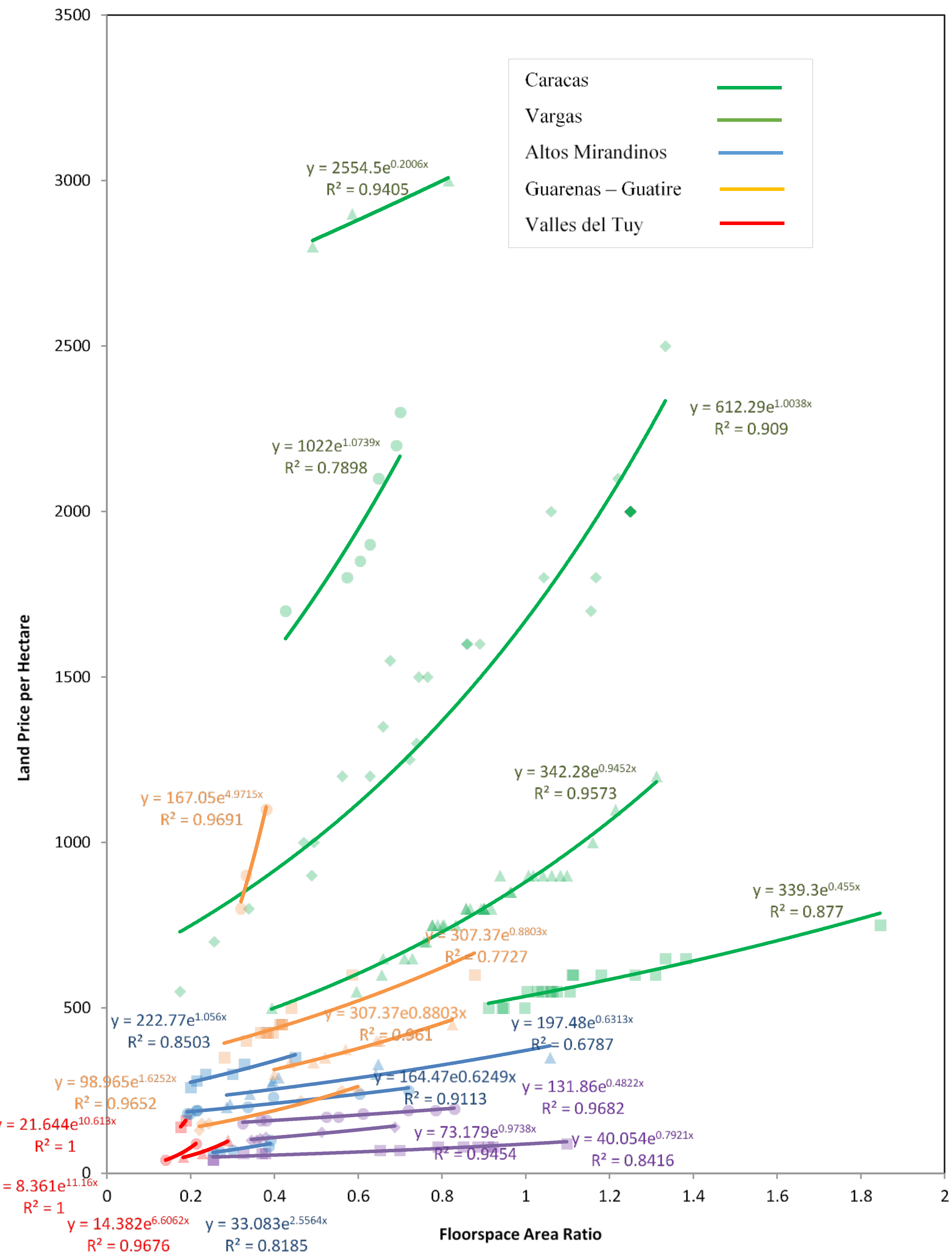


Figure 8. Relationship between land price and FAR for single family residential

Step 3. Generating synthetic households, residential and non-residential space use rates

For Caracas, employment data are reliable and available for every individual based on the 2001 National Census. Employees by place of work and by zone are available from previous studies developed by Instituto de Urbanismo (Insurbeca, 2007). These employment records by industry were split based on occupation into those using production space (e.g., industrial) and those in office space. Total employment and floor space were used to generate the non-residential space use rates for the Region (Table 4).

Table 4. Space Use rates for non-residential floor space

Space use rates for non-residential space (m^2/employee)			
Non-residential Floorspace category	Employment	Floor Space	Space Use Rate
Retail	168,950	2,895,934	17.14
Office-retail	936,902	11,753,291	12.54
Hospitals	45,333	2,148,860	47.40
Higher education	68,429	4,035,240	58.97
Primary education	129,053	2,248,840	17.43
Industrial – Retail	345,160	11,226,879	32.53
Industrial	366,188	20,035,189	54.71
Utilities	3,750	6,368,581	1,698.14
Sociocultural	52,904	2,093,394	39.57
Agriculture	20,958	1,806,626	86.20
Government	90,897	3,096,939	34.07
Total	2,228,528	67,709,773	

Household data for Caracas were available from several sources, but the Census does not report housing type in the slum areas nor the size of dwelling units, so establishing residential space use rates was challenging. This was addressed using a population synthesizer, where a complete population representation was obtained by combining a sample of households from the 2001 Census to match key distributions of targets by geographies for the entire population of households.

The sample size for this application in Caracas was around 30% of the population of households, which is several times higher than the sample available from the Census in the United States or Canada. Having a sample of this size helps in obtaining a good fit to the defined targets (Table 5).

Table 5. Population synthesis variables and their targets

Variable	Targets	Geography type	Source /Date
Amount of Residential space (m^2)	Slum Single Family Residential (SFR) Multifamily Residential (MFR)	LUZ	Estimated Floor space
Estimated number of dwelling units for 2007	Number of units	LUZ	Census / 2001 Projected to 2007
Apartment distribution	% of apartments	LUZ	Census / 2001
Household size (% of households with a number of people in the dwelling unit)	0 people, 1 people, 2 people, 3 people, 4 people, 5 people, 6 people, 7 people, 8 and plus people	Parroquia (group of LUZ)	Census / 2001
Socioeconomic level (% of households by socioeconomic level)	Out of poverty In poverty In extreme poverty	Macrozone (group of LUZ)	Household Survey / 2005

The size of the dwelling units in each sample was unknown; it was imputed by applying multiple regression models using observations provided by a Century21 office in Caracas. The dwelling size was calculated using Equation 2 as follows:

$$Size_{D,S} = e^{LocConsD,L} \times (1+NumBdrms)^{Coeff\ LogBdrms} \times (1+NumWash)^{Coeff\ LogWash} \quad (2)$$

Where:

$Size_{D,S}$	= Predicted space quantity for a dwelling unit in the sample table
$LocCons_{D,L}$	= Location constant vary depending on unit type and location
NumBdrms	= Number of bedrooms in the dwelling unit
Coeff LogBdrms	= Coefficient for the [logarithm of the number of bedrooms]
NumWash	= Number of washrooms in the dwelling unit
Coeff LogWash	= Estimated coefficient for the logarithm of the number of washrooms

This step of the process was repeated several times, changing the configuration of the target data and the synthesizer features and settings (e.g., number of times a sample can be use in the output) to improve the goodness of fit of the estimation. The final synthesis matched the targets well, having a good fit for dwelling counts at the expense of some mismatch for socioeconomic level.

The average residential use rates by household type are shown in Figure 9. This step developed the following elements of Table 2: *Floor space by zone, Spatial distribution of activities* for households, and provided *Observations of technology choice* for households choosing quantities and types of residential space. It also partially contributed to the element called *Put definition*.

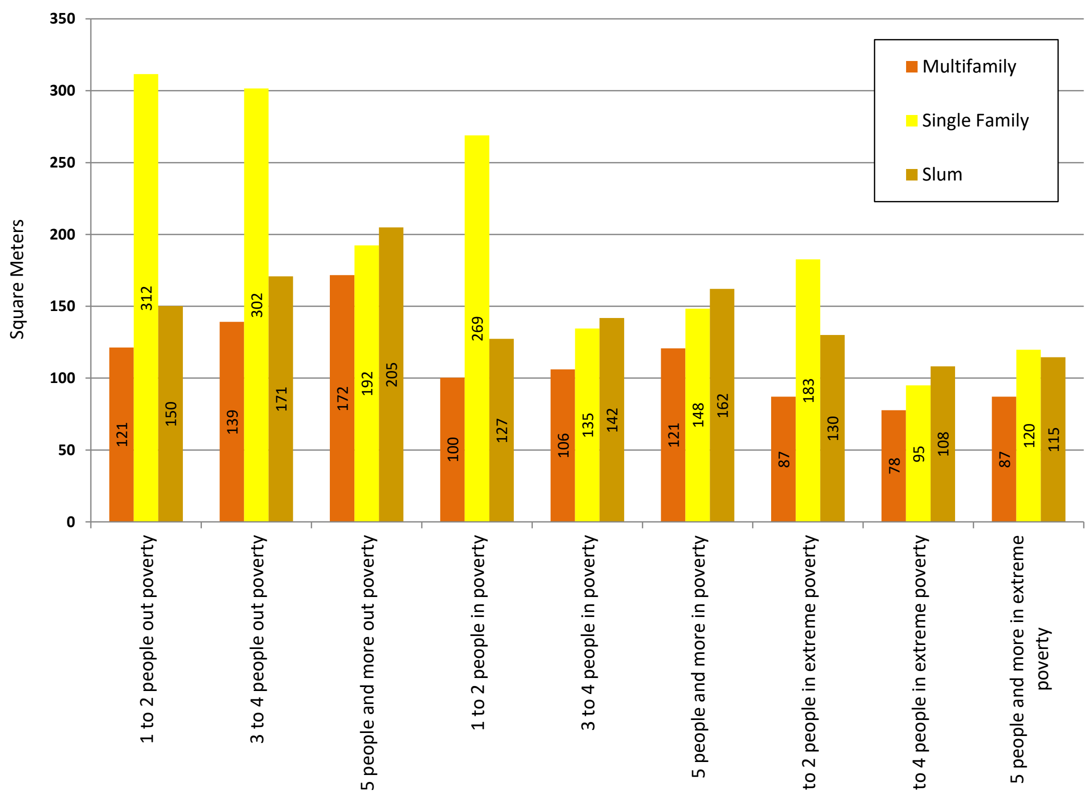


Figure 9. Residential space use rates by space type and by household category (m^2 per household)

Step 4. Completing the Design Diagram

An overview of the Design Diagram for Caracas (Figure 10) shows colored blocks for the relationships included in this model. The main interactions studied are industries producing and consuming goods and services, and consuming labor and space; and households consuming goods and services, providing labor, andconsuming space. The production of labor and the consumption of space were made elastic.

The categorization of industries was derived from aggregations of industry categories reported in the Input-Output table and in the Census data, as well as how employees in these industries use office space and production space (Table A-1 of Appendix 1). The categorization of labor corresponds to aggregations of the categories reported by the National Census, as well as the salaries paid by industry and the space used by the employees in the workplace from Step 3 (Table A-2 of Appendix 1).

The categories of goods and services were defined as aggregations of the categories reported in the Input-Output Table (IOT) of Venezuela (Table A-3 of Appendix 1). Aggregations were based on similarities between the products, considering the size of production and consumption in each category. Floor space categories are presented in Table A-4 of Appendix 1.

This step develop four elements of Table 2: *Activity definitions, Put definitions, Design Diagram* and*, Built form.*

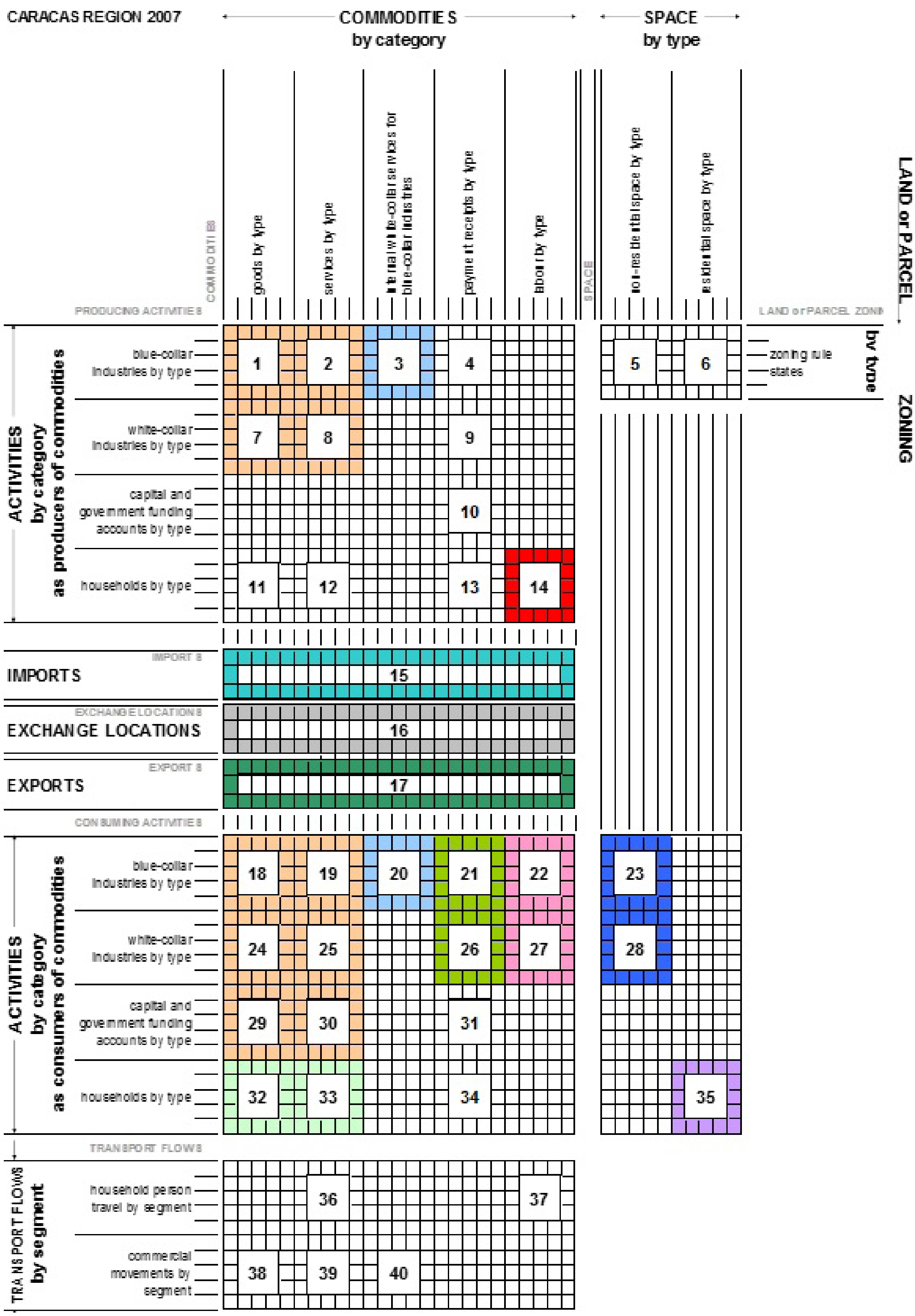


Figure 10. Overview of the Design Diagram for PECAS Caracas model

Step 5. Developing the Aggregate Economic Flow Table (AEFT)

Developing the aggregate economic flows for Caracas, following the Design Diagram, involved many tasks and data sources.
First, the national Input-Output table (IOT) of 1997 (Banco Central de Venezuela, 1997) was processed by:

- Generating a production matrix with simplified categories of industries, goods and services;
- Adding the utilization matrix and imports to generate the consumption matrix;
- Identifying other sections: Imports, Exports, Use by Institutions and Taxes.

The resulting Make and Use table for the country has three sections: Supply (Make and Import sections), Demand (Use section, the Exports, and the Use by Institutions) and Taxes.
To further process the Make and Use table and apply it to the Caracas region for 2007, we:

- Updated the 1997 Input-Output table by assuming rates for the production and consumption of puts were still valid in 2007;
- Scaled the IOT from the nation to the Region using employment data from the Census;
- Split wages into occupation categories, for both labor used by industries and labor made by households using salary indexes (Banco Central de Venezuela, 2014).

Each matrix represents the aggregate quantities of interactions between an activity and its puts (goods, services, labor and space), as either production (outputs) or consumption (inputs). All of them comprise the resulting *Aggregate Economic Flows of puts among activities*. This step also completed the element called *Imports and exports* from Table 2.

Note that the money amounts of the AEFT is employed to generate rates of production and consumption of the industries and households in the region and is one of the most important elements for the AA module.

Step 6. Estimating the transport cost coefficients

The utility of transporting a unit of each put category is based on zone to zone measures of transport attributes from a transportation model. The form of the transport utility is:

$$\mathrm{Tran}_{c,j,k} = \kappa_{1c} \cdot \mathrm{IntAtt1}_{j,k} + \kappa_{2c} \cdot \mathrm{IntAtt2}_{j,k} + \kappa_{3c} \cdot \mathrm{IntAtt3}_{j,k} + \kappa_{4c} \cdot \mathrm{IntAtt4}_{j,k} \quad (3)$$

Where:

$\mathrm{Tran}_{c,j,k}$ = the utility of transporting a unit of put *c* from zone *j* to zone *k*;
$\mathrm{IntAtt}_{n,j,k}$ = the value of interchange attribute *n* from zone *j* to zone *k*;
κ_{nc} = the utility function coefficient representing the sensitivity to attribute *n* when transporting a unit of put *c*;
n = the index for the interchange attribute (e.g., 1=distance, 2=time, 3=money cost);

The data used to develop the transport cost coefficients for this model of Caracas are shown in Table 6.

Table 6. Inputs used to calculate the transport cost coefficients

Put code	Type of put and type of interchange	Inputs for the Caracas model	Source of Data
CG01_Ag	Goods	-Cost per weight (Bs/ton) per put -Average use of truck capacity by put and by type (capacity) -Cost per minute (Bs/min) per type of truck -Cost per kilometre (Bs/km) per type of truck -Distribution of trucks by put and by type (capacity)	United States Census Bureau, 2000 and Standard Classification of Transported Goods
CG02_MiQuO&G			
CG03_ManLtInd			
CG04_ManHvyInd			Cámara de Transporte del Centro – CATRACENTRO. This is a private organization of transportation companies that operates in Caracas and the center of the country
CS01_Util			
CS02_Const			
CS03_WhReTrd			Cal & Mayor - Plan de Ordenamiento Logístico de Bogotá, 2005
CS04_Tr&Whg			
CS07_MangComEnt	Worker delivered service puts	-Annual consumption (money value) of puts by households -Number of annual visits by purpose -Transport money cost coefficient	AEFT for Caracas
CS06_Prof&Tech			Modelistica, 2005 – Mobility Survey for the Caracas Metropolitan Area
CS13_IntManag			TRANUS Mathematical Description
CS08_Governm	Household obtained service puts	-Distribution of annual wages paid to occupations by socioeconomic level (out of poverty, poverty, extreme poverty) -Total number of annual trips by socioeconomic level -Transport money cost coefficient	AEFT for Caracas
CS09_EducServ			Modelistica, 2005 – Mobility Survey for the Caracas Metropolitan Area
CS10_Health			
CS11_OrgEmp			TRANUS Mathematical Description
CS12_EntMedCult			
CS05_FIRE			
CL01_Manag	Labor puts	-Annual production (money value) of puts by industries -Number of annual visits by purpose -Transport Money Cost Coefficient	AEFT for Caracas
CL02_Medical			
CL03_HighEduc			Modelistica, 2005 – Mobility Survey for the Caracas Metropolitan Area
CL04_PrmryEduc			
CL05_Sales			
CL06_Manuf			TRANUS Mathematical Description
CL07_Drivers			
CL08_AgricWkers			

This step created the element from Table 2 called *Transport costs*.

Step 7. Generating transport skims for Caracas

A transport model of Caracas was previously developed using TRANUS and it was generously provided for this work (Modelistica, 2008). Skims for time and distance were used directly for the Goods. The generalized cost skims from TRANUS were used to calculate the composite cost under the standard logit approach. These skims were used for the rest of the puts. This transport model includes a detailed representation of the public transport system, which is important because the use of transit is around 57% for the Caracas subregion (Modelistica, 2005). The model represents the passenger movement by all modes, including the travel taking place in the slum areas. For labor, the TRANUS model representation of travel cost sensitivity for the purpose of work in three separate socioeconomic categories were used.

A transport model for Venezuela, also developed with TRANUS, provided data on trips by trucks, which were used to estimate the transport coefficients for the Goods (Modelistica, 2013).

These two TRANUS models had been calibrated to observed data on travel, including a travel survey and screen line counts. Travel matrices and trip length distributions from these models were explored and they were found to be consistent, and consequently used as targets for calibrating the flows of puts.

This step partially developed the element from Table 2 called *Flows of puts*.

Step 8. Estimating rents by space type

Families in Venezuela tend to own properties instead of renting because of the high inflation rate. Rents in PECAS still apply to homeowners—they represent the opportunity cost of the income that the owner forgoes by not renting out the property—but the rarity of renting makes it difficult to collect enough rent observations for a proper estimation. To overcome this issue, two estimations were connected: an estimation of land prices (Insurbeca, 2007), and an estimation of rents.

5.1 Estimating land prices

Graphical plots were used to investigate the correlation between land prices and construction densities for each space type. As an example, Figure 8 shows the patterns and correlations that were identified within groups of zones sharing the same subregion and quality for the single family residential space.

The clustering of zones in Figure 8 implies a similar attractiveness within each residential submarket. These submarkets have similar zonal constants (V_l in Equation 1), representing influences not included in the utility of exchanging puts, such as crime rates and the age and quality of the buildings.

Ninety-eight price functions were defined for residential and non-residential space clusters.

5.2 Estimating rent by space type and by zone

To convert annual land prices into annual rents, regressions were estimated for each space type. Observations of 2014 rents by space type from Century 21 and inflation rates were employed to calculate rents for 2007. The resulting correlations were between 0.75 and 0.99 for all the space types.

The estimated rent functions were applied to calculate annual rent per area by space type and by zone for 2007. As an example, rent patterns for multifamily residential were found to be higher in the eastern and southeastern parts of the Caracas subregion, as expected (Figure 11).

Step 8 developed the element *Observed prices by zone* from Table 2.

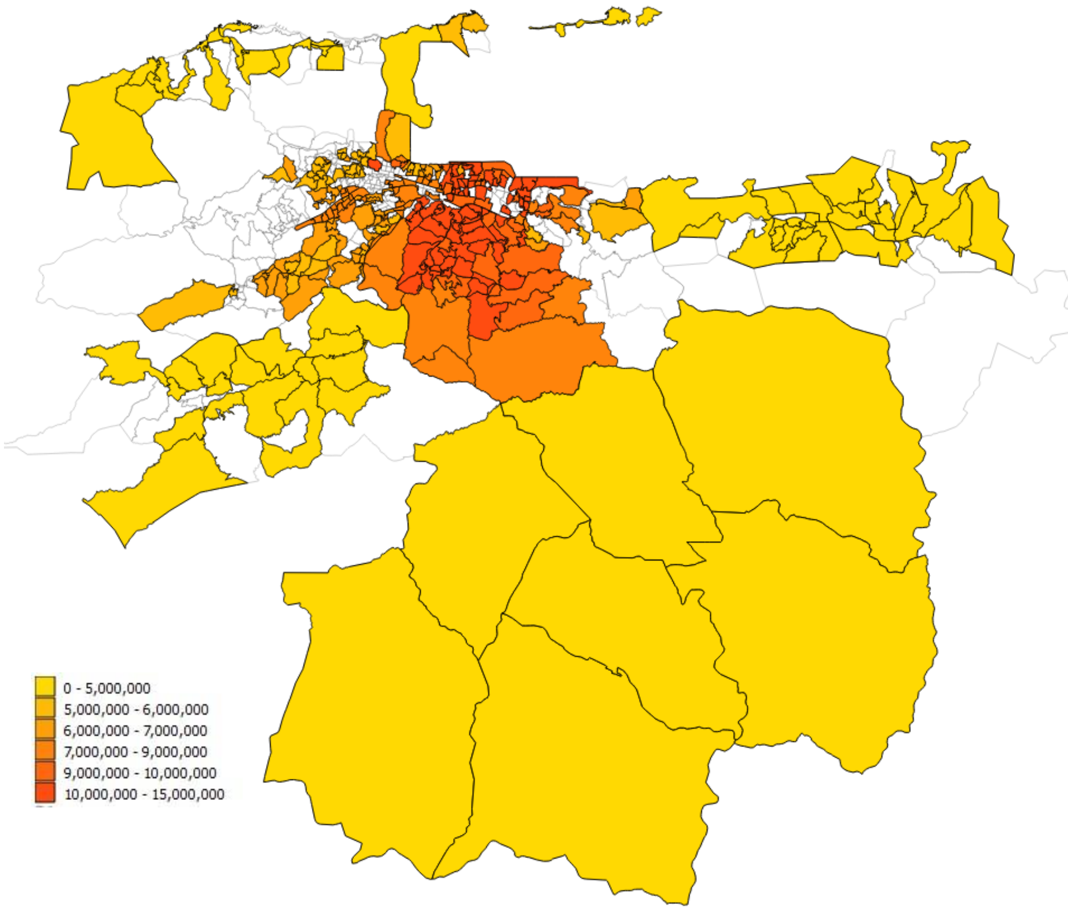


Figure 11. Rents (Bs/m^2) for multifamily residential

Step 9. Landlord behavior functions by space type

Landlord behavior functions allow AA prices to extrapolate beyond rent observations – 0% occupancy at low prices and over 100% occupancy at extremely high prices – while still accurately producing typical occupancy rates at typical prices. Average occupancy rates for residential types were estimated by zone using the 2001 Census data. These functions were calibrated and adjusted in form to be able to work with Venezuelan currency. The extrapolations for two slum types are shown (Figures 12 and 13).
Step 9 developed the element *Short-term floor space supply functions* from Table 2.

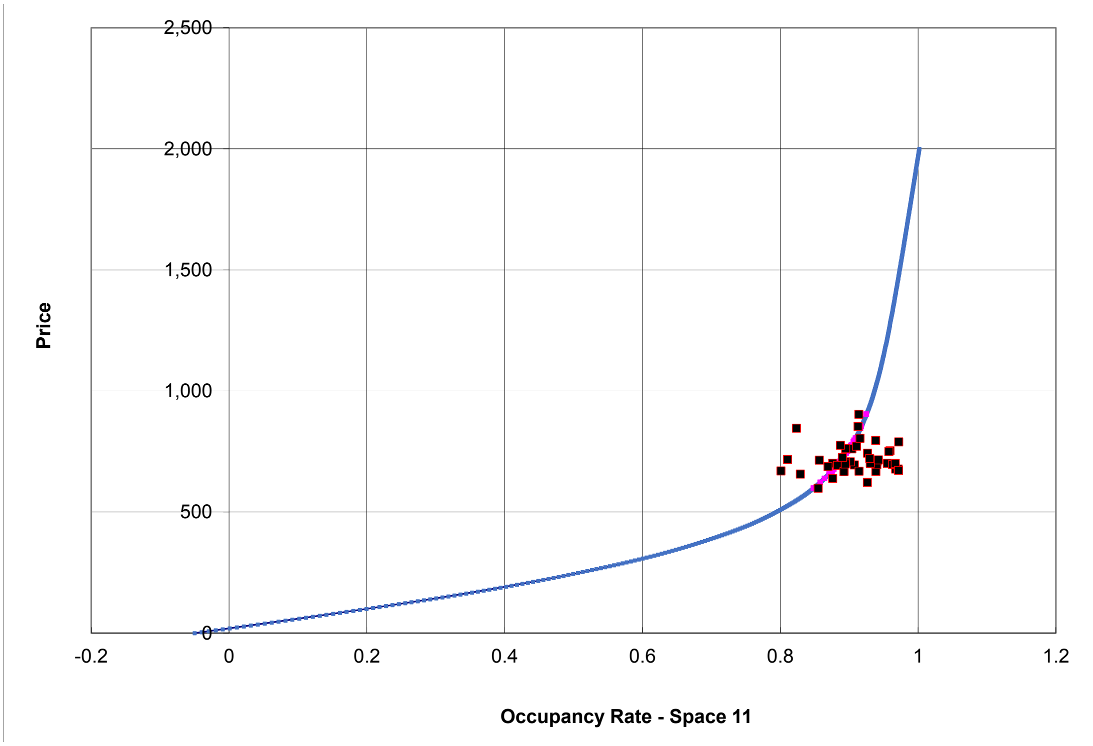


Figure 12. Landlord behavior function for Slum_11

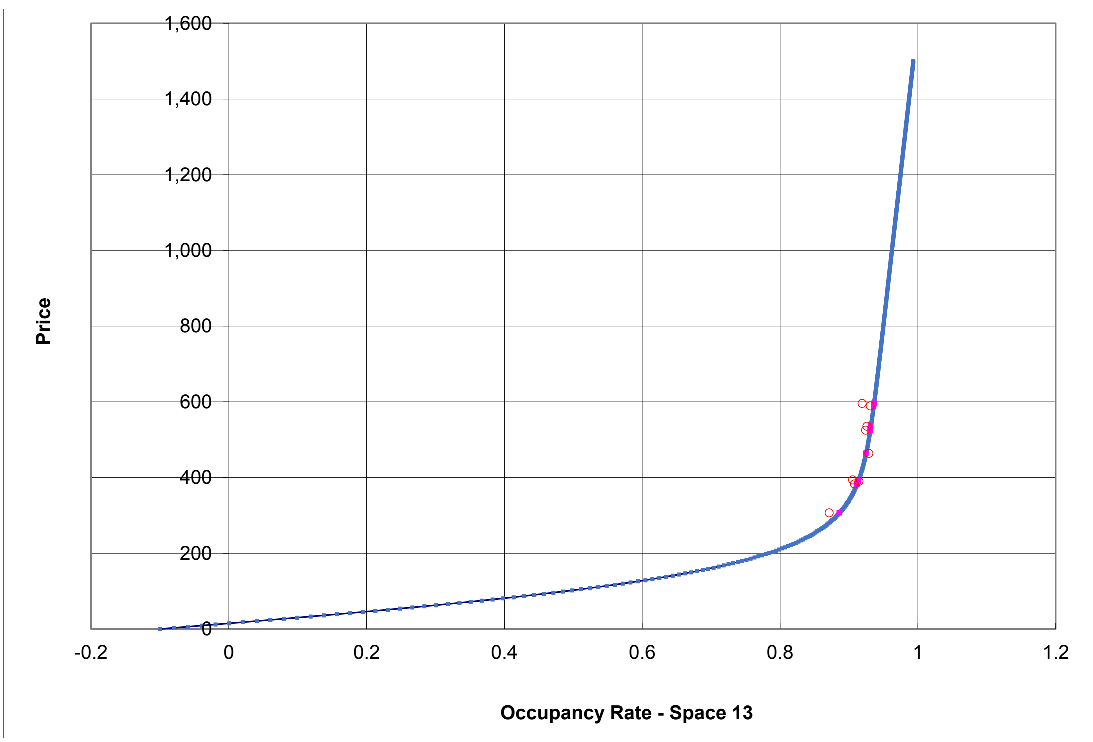


Figure 13. Landlord behavior function for Slum_13

Step 10. Running the AA module

The elements from Table 1 were assembled and formatted into input files for AA, which undertakes a price search to represent the base scenario short-run equilibrium. The model was run, and it was able to *converge* – balance supply and demand for each put by adjusting prices. Adjustments were made based on diagnostic messages. These adjustments were revisited during calibration (Step 11).

Step 11. Calibrating the model

The term calibration refers to the process of establishing parameter values and constants that better allow the model to reproduce the observed conditions, without compromising any important components of the model.

The calibration approach involved estimating parameters in several stages. Stage 1 parameters were estimated once using data from outside of the model (e.g., technical coefficients, transport cost coefficients and floor space supply function parameters); Stage 2 parameters were refined by comparing module output files to targets based on observations, and this stage must be revisited each time the model is adjusted. The three types of Stage 2 calibration performed in the AA module are summarized in Table 7.

Table 7. Parameters and targets for Stage 2 by calibration type for the Caracas model

Calibration type	Parameter or values adjusted	Targets
Trip Length (TLC)	-A parameter that controls the sensitivity of buyers and sellers of each put to differences in desirability between exchange locations	-Average trip length for the goods, and average trip time for the services and labor
Option Weight (OWC)	-A constant associated with each technology option for each activity	-Proportions of households by category with labor occupations and average use of residential space -Proportion of non-residential space used by industry -Amounts of imports and exports for import providers and export consumers
Floor space (FSC)	-Space quantities by space type and zone	-Observed quantities of space with confidence intervals -Estimated rents by zone with confidence intervals -The relative priority of matching observed space quantities and matching estimated rents depends on the reliability of each for a given space type and zone, as represented by the confidence intervals

Stage 2 calibration is iterative. The simultaneous equilibrium nature of the system connects every output to every input, so that adjusting some parameters to match some targets affects previous calibration efforts. The sequence and cycles of calibration for Caracas are shown in Figure 14.

The results of Trip Length Calibration (TLC) are shown in Table 8. In general, the model reproduced the observed quantity of travel. For goods categories, the largest mismatch was in mining and agriculture. This was accepted due to the small size of these primary industries in Caracas, and a lack of confidence in the low distance targets. For labor, the commuting times of drivers and manufacturing employees show the largest mismatch.

In the Option Weight Calibration (OWC), the weight represents the a *priori* probability of a choice, and extremely large or small values suggest extreme preferences and may indicate unreasonable choice functions that should be investigated. As an example, observations of impoverished people working as live-in housekeepers led to unrealistic weights for large luxury dwellings and extreme poverty. This was investigated and removed, with the recognition of the associated model limitation.

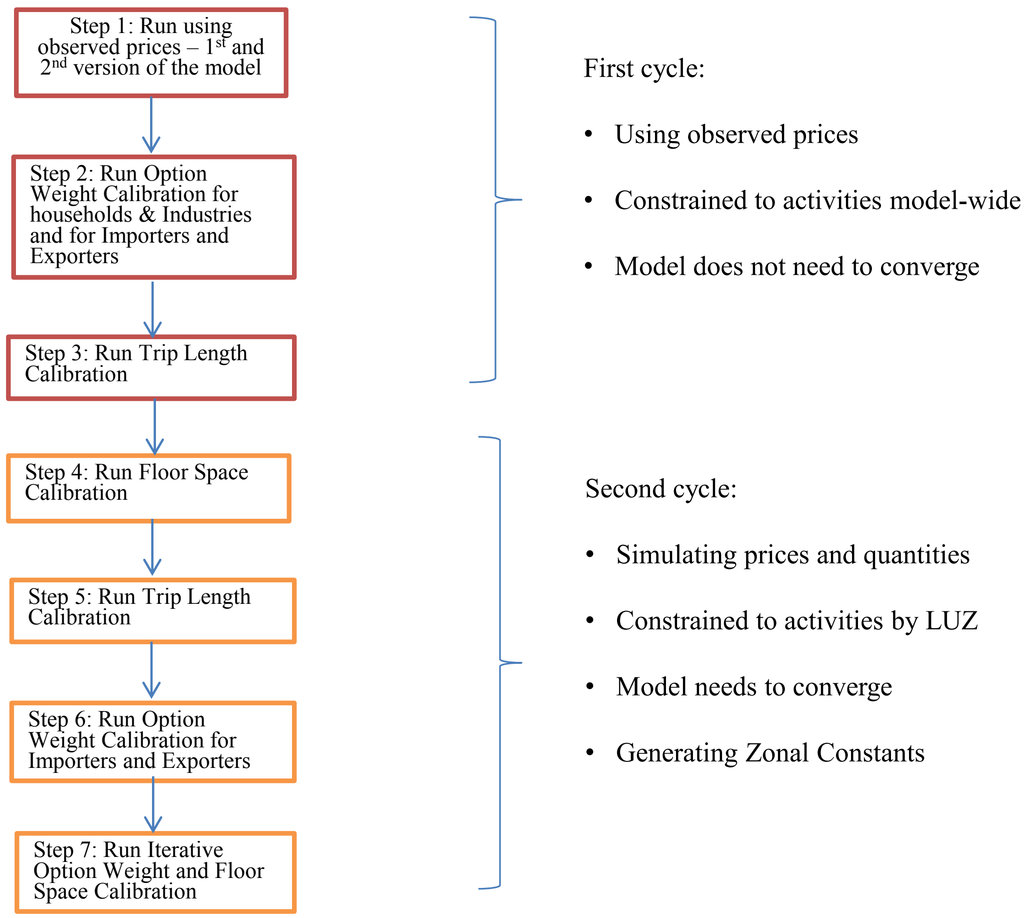


Figure 14. The calibration sequence followed for the Caracas Region

Table 8. Trip length calibration results (running to convergence)

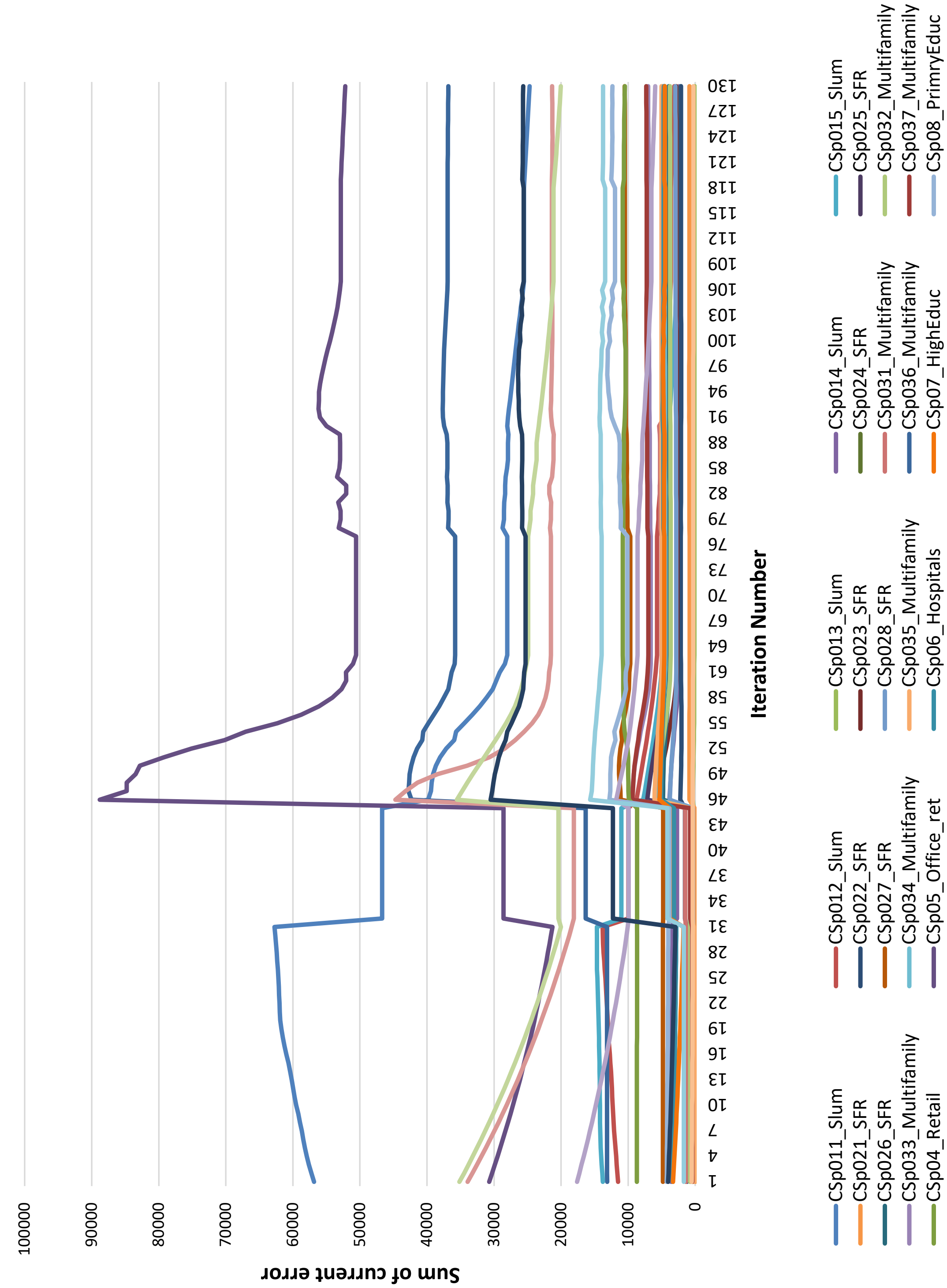
Put Category	Parameter	Target	Model	Error	Model minus Target	Units
CG01_Ag	16.53	25.00	35.82	43%	10.82	km
CG02_MiQuO&G	1.37	18.00	30.42	69%	12.42	km
CG03_ManLtInd	112.82	25.00	28.68	15%	3.68	km
CG04_ManHvyInd	27.48	25.00	27.50	10%	2.50	km
CS01_Util	5.00	18.00	25.78	43%	7.78	km
CS02_Const	2.76	20.00	25.20	26%	5.20	km
CS03_WhReTrd	150.00	25.00	26.66	7%	1.66	km
CS04_Tr&Whg	92.31	25.00	27.52	10%	2.52	km
CS05_FIRE	1.10	25.00	23.66	-5%	-1.34	km
CS08_Governm	13.00	35.00	30.36	-13%	-4.64	km
CS09_EducServ	13.46	25.00	20.31	-19%	-4.69	km
CS10_Health	13.00	25.00	22.67	-9%	-2.33	km
CS11_OrgEmp	4.80	30.00	30.28	1%	0.28	km
CS12_EntMedCult	19.13	23.00	25.18	9%	2.18	km
CS06_Prof&Tech	150.00	25.00	25.14	1%	0.14	km
CS07_MangComEnt	1.10	25.00	24.54	-2%	-0.46	km
CS13_IntManag	87.56	23.00	22.02	-4%	-0.98	km
CL01_Manag	150.00	135.00	136.89	1%	1.89	Minutes
CL02_Medical	27.88	115.00	116.03	1%	1.03	Minutes
CL03_HighEduc	27.64	105.00	108.00	3%	3.00	Minutes
CL04_PrmryEduc	43.05	120.00	118.59	-1%	-1.41	Minutes
CL05_Sales	96.81	130.00	133.08	2%	3.08	Minutes
CL06_Manuf	150.00	130.00	148.60	14%	18.60	Minutes
CL07_Drivers	25.14	93.00	103.78	12%	10.78	Minutes
CL08_AgricWkers	27.43	93.00	99.34	7%	6.34	Minutes

Figure 15 shows the evolution of goodness of fit during the Floor Space Calibration (FSC). Two minimum points can be observed: one at iteration 30 and another at iteration 45. Based on expert opinion, results from iteration 45 were chosen.

The weakest link during the space calibration was the centrally-located slums. This space is difficult to represent because it is cheaper, yet better located than other residential types, making it an attractive option. But the social stigma and the cultural aspects of slums repel some households, but not others who are familiar with that environment.

Step 11 developed one element from Table 2: *Flows of puts*.

Figure 15. Evolution of the error from the floor space calibration (weighted squared error, all space types)



Step 12. Performing sensitivity tests

The objective of sensitivity tests is to show how the model responds when changes are introduced into the spatial economic system. Two policies already applied in the Caracas Region were tested: 1) provision of public housing, and 2) an increase in transit fare. These tests measure changes in consumer surplus between the base scenario and the alternative scenarios.

5.3 Scenario analysis

In the ***Public Housing scenario***, 21,000 new apartment buildings of 70 m^2 are provided. This was implemented in 2010 mainly to compensate for housing destroyed during the rainy season.

The ***Transport Cost scenario*** involves a 40% increase in transit fares in 2015 (El Nacional, 2015) affecting personal trips for the purposes of work, education, health, commerce, and services. New skims were calculated by adjusting the composite cost.

Scenario results are summarized below:

In the ***Public Housing scenario***, housing rents decreased for most of the housing types – with a larger impact for low quality and mixed multifamily (between 8 to 12%), single family with medium quality (2 to 20%), and centrally-located slums (2 to 10%). This effect is positive for the households renting units in these space types, which are also more spatially concentrated in the Caracas subregion, but negative for homeowners. Changes in rents by zone are shown in Figure 16.

In the ***Transport Cost scenario***, both households and industries lose benefits, with households bearing 73% of the lost benefits.

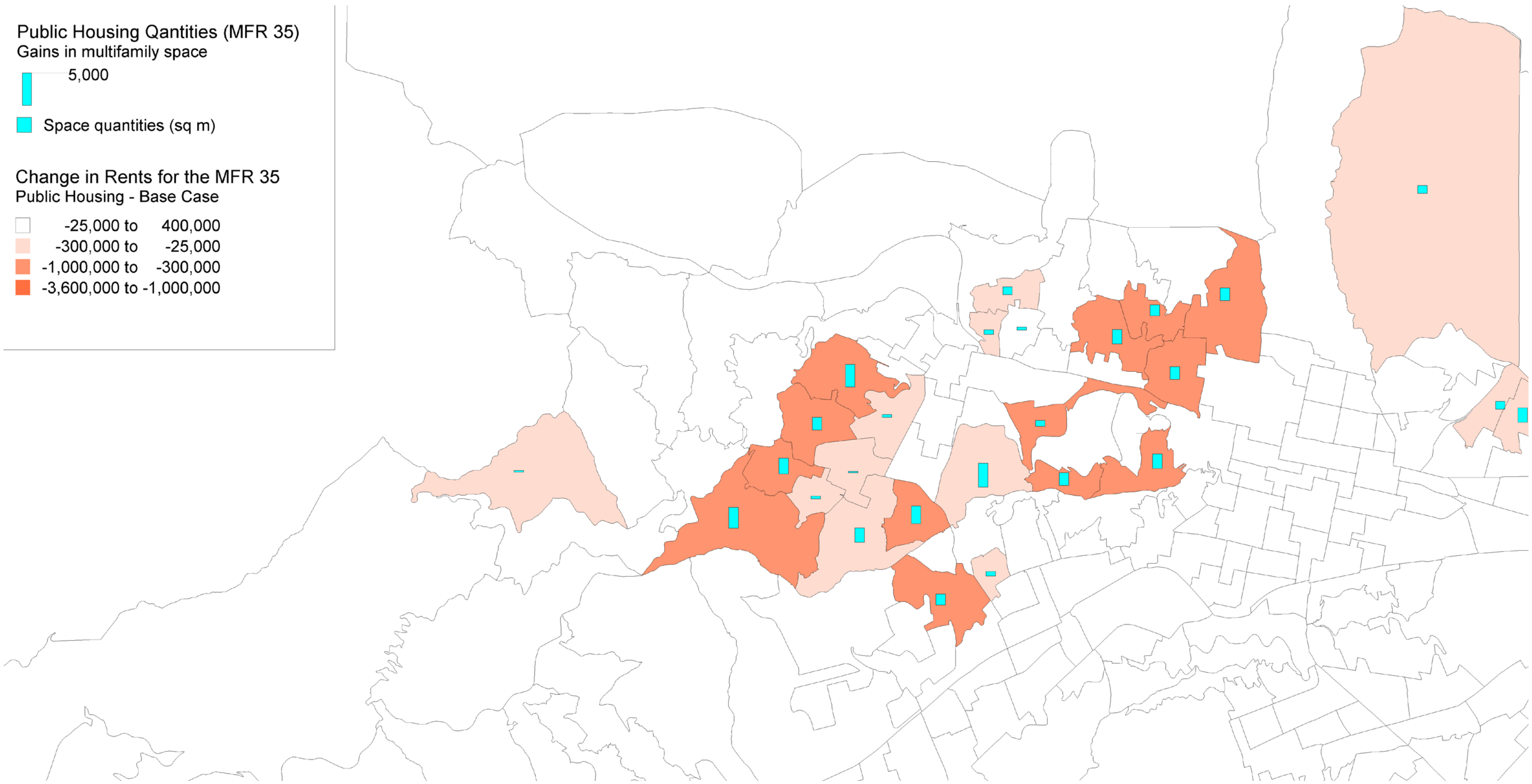
For households:

- Households travelled shorter distances, reducing commuting trip length by 3 to 20 km depending on the occupation, and were paid higher salaries to compensate for their additional commuting cost.
- The greatest losses in accessibility appeared for households consuming Education and Health Services, who travelled to closer facilities, because the options they otherwise would have chosen had too high travel costs.
- Residential rents increased in central locations (Caracas subregion) and decreased in the other subregions. Some families relocated to smaller or lower quality housing in central locations, or to less attractive zones outside of the Caracas subregion, resulting in a re-sorting of families according to income, reinforcing spatial and social segregation in the Region (Figure 17).

For businesses:

- The Education industry gained benefits due to an increase in local demand (less need to compete), and smaller salaries were paid to some of their employees.
- Some businesses changed location, choosing to use less space and/or other space types to minimize the impact of wage compensation to attract employees.

Figure 16. Space quantities gained for the MFR 35 (Low quality) and changes in rents in central areas of Caracas in the public housing scenario



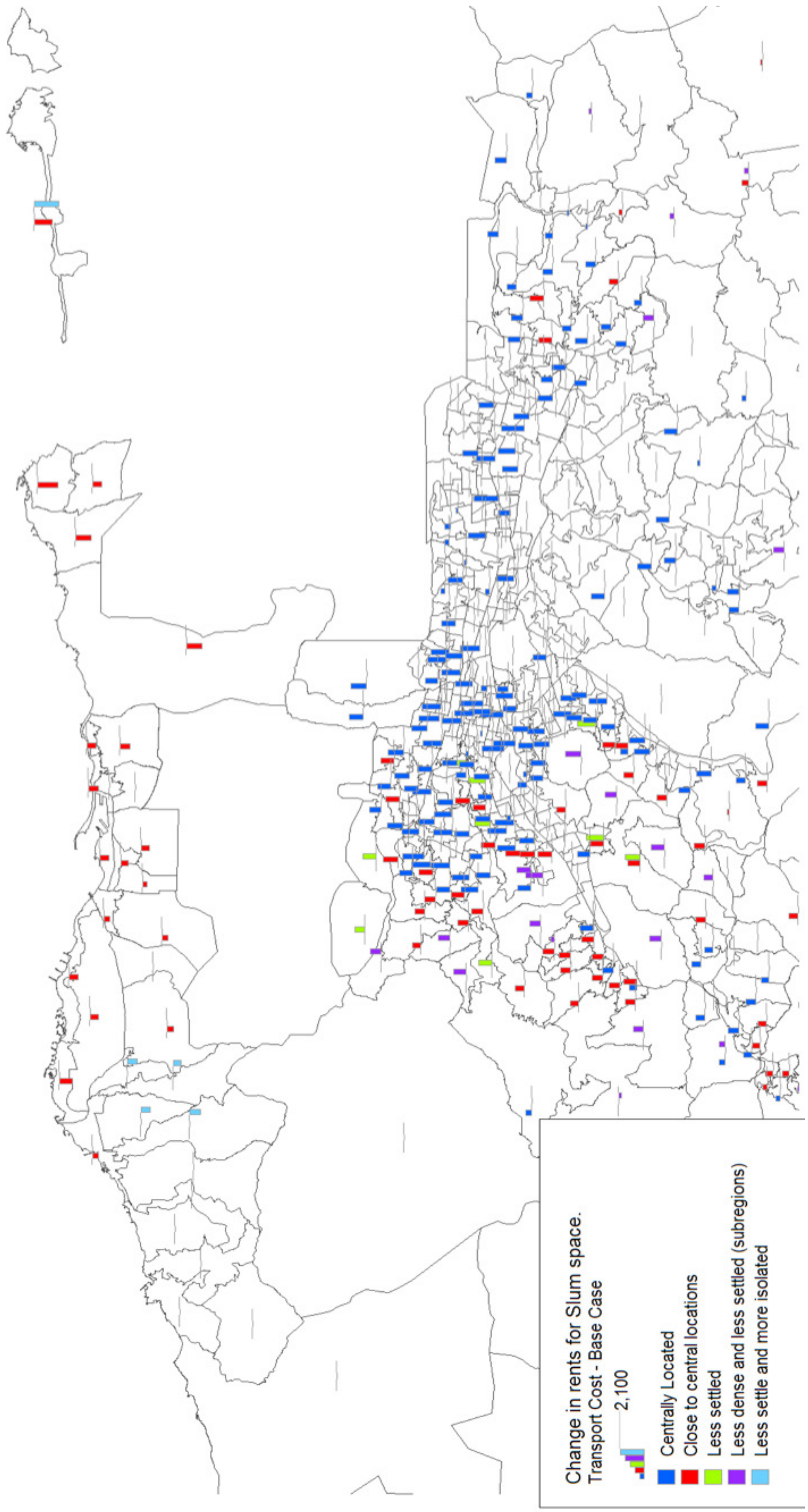


Figure 17. Changes in annual rents by zone for slum space in the Vargas and Caracas subregions in the transport cost scenario

6 Findings and conclusions

The development of the PECAS model for Caracas was a research project that took around five years (2010 to 2015). It included testing different datasets until we found data and techniques that worked well, including the adoption and adjustment of transport models developed with TRANUS. We believe this experience brings important know-how to the modelling field, including sources and techniques that could save future modelling teams both time and money. Specifically:

- The technique to synthesize households proved to be successful in developing two main data elements: an inventory of the space quantities by zone, and the residential use rates.
- When data required to develop a certain model component were not available, incomplete, or inconsistent, our strategy was to: a) borrow data from a similar region; b) borrow data from where they are available and adjust them to the study area; c) keep looking for new data to validate, combine with, or replace the original data; d) share our thoughts with researchers who are more experienced in specific topics; e) explore the data from different datasets, by themselves and in combination – when correlations and patterns become evident, insights can arise.
- This was the first time PECAS and TRANUS had been used together, with TRANUS transport disutilities used in PECAS for the costs of spatial economic interactions between activities. The policy sensitivity test showed the reasonableness of the zone-to-zone travel attributes calculated by TRANUS.
- Having 20 residential space types made calibration challenging. A model with around 10 categories would represent the residential heterogeneity in Caracas, and the model's response in space consumption may have been more realistic and would have been easier to interpret.
- The importance of the service categories that emerged in the policy tests suggests that some puts, such as Education and Health, should be further divided to better represent the difference in quality and in the affordability of different classes of service by different types of households.
- Even though the calibration worked well in general, we noticed from the sensitivity test that the model seemed to overrespond in two ways: a) households with employment in Higher Education reacted more strongly in the labor market to transportation cost changes than we would expect, and b) The activity allocation module represents a short-term (one year) equilibrium in the occupation of space by activities, but long-serving institutions (e.g., cathedrals, central libraries, hospitals and universities), do not react over a one-year time frame. These two aspects could be improved.

Caracas is a region with a history of social turmoil, riots, drastic currency changes, high unemployment rates, high inflation rates and high crime rates, with substantial poverty and social issues. Many of these things were appropriately represented in our calibration data, but we did not anticipate that 40 years of stable high inflation rates (always around 20%) would suddenly jump from 60% in 2014 to 500% in 2016, and from there to more than 1,000,000% in 2018. In the last four years the country has experienced a massive population emigration, shortage of food, electricity and water cuts and a humanitarian crisis, and the data we used to calibrate the model do not represent these recent events, which began just after the model calibration was completed. We now do not feel that the existing model is useful for future scenario analysis in Caracas. Time is critical for any model, particularly in contexts dominated by economic and political volatility. In hindsight the 5 years development program was too long to produce a model useful for influencing future policy. It is hoped that this experience exposes sources and techniques that worked well in Caracas, and that future modelling teams could employ these sources and techniques to save both time and money, delivering models that can be effective even in volatile cities and regions.

References

Abraham, J. E., & Hunt, J. D. (2007). Random utility location, production and exchange choice: Additive logit model and spatial choice microsimulations. *Transportation Research Record: Journal of the Transportation Research Board, 2003,* 1–6.

Banco Central de Venezuela. (1997). Matriz insumo producto año 1997 [Government site]. Retrieved from http://www.bcv.org.ve/cuadros/series/mip97/mip97.asp?id=425

Banco Central de Venezuela. (2007). Indice mensual de precios al consumidor Area Metropolitana de Caracas [Government site]. Retrieved from http://www.bcv.org.ve/c2/indicadores.asp

Banco Central de Venezuela. (2014, June 27). Indice de remuneraciones [Government site]. Retrieved from http://www.bcv.org.ve/estadisticas/indice-de-remuneraciones

El Nacional. (2015, February 13). Oficializan aumento de 40% en transporte público. Retrieved from http://www.el-nacional.com/economia/Oficializan-aumento-pasaje-transporte-publico_0_574142627.html

Fuenmayor, G. (2016). Building a spatial economic model for Caracas using PECAS (PhD, University of Calgary). Retrieved from http://hdl.handle.net/11023/3061

Hunt, J. D., & Abraham, J. E. (2009). PECAS – for spatial economic modelling: Theoretical formulation. Retrieved from http://www.hbaspecto.com/

Hunt, J. D., & Abraham, J. E. (2005). Design and implementation of PECAS: A generalized system for allocating economic production, exchange and consumption quantities. In *Integrated land-use and transportation models: Behavioral foundations.* Amsterdam: Elsevier.

Insurbeca. (2007). Estudio Socio-Económico y Urbano-Regional del ámbito espacial del metro de Caracas. Caracas: Insurbeca.

Martinez, J. (2007). *Terrain model of the Caracas region*. Caracas: Instituto de Urbanismo, UCV.

Modelistica. (2005). Planificación y Diseño de una red Integrada de Transporte Público para el Área Metropolitana de Caracas red mayor. Fase I - Estudio de Movilidad. Caracas: Alcaldía del Distrito Metropolitano de Caracas.

Modelistica. (2008). Estudio de Demanda para la prolongación de la Línea de Metro de Caracas-Los Teques. Retrieved from https://sites.google.com/site/modelistica/caste/proyectos

Modelistica. (2013). Transporte de fosfatos en Tachira, Venezuela. Retrieved from https://sites.google.com/site/modelistica/caste/proyectos

National Bank of Canada, F. M. (2018, October 1). Geopolitical briefing. Economics and strategy. Retrieved from https://www.nbc.ca/content/dam/bnc/en/rates-and-analysis/economic-analysis/GeopoliticalBriefing_181001.pdf

Trading Economics, E. (n.d.). Venezuela inflation rate. Retrieved March 12, 2019, from https://tradingeconomics.com/venezuela/inflation-cpi

Appendix

Appendix A available as a supplemental file at www.jtlu.org/index.php/jtlu/rt/suppFiles/1188/0.