

Multivariate Statistical Analysis for the Assessment of Potential Energy Savings in Low-Density Urban Building Stocks in the City of Mendoza, Argentina

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ABSTRACT: The present study's goal is to contribute knowledge and methodology to the assessment of the potential energy recovery for space heating, retrofitting existing building stocks in low-density urban environments of Mendoza's Metropolitan Area.

The morphological features of the built environment, urban and architectural, combined with the technological alternatives of the existing buildings, were analyzed for the reference situation (present without changes) and for a theoretical improved condition, massively implementing increased conservation measures and additional passive solar gain. Three indicators were selected to assess the significance of the solar contribution: 1. the masking of potential collectors by neighbouring obstructions, 2. the useful fraction of the total energy received on a given urban area and 3. the potential savings obtainable by the massive recycling of the buildings.

In a first stage, the solar contribution was determined by the use of a graphic-computational model and, in a second stage, given the complexity and interrelationships of morphological variables, the results were analyzed through the use of a statistical multiple linear regression model, which yielded two useful results per indicator (response variables): 1. a simple calculation tool (equation) to infer values for each of the three indicators (response variables) and 2. a hierarchical order of the most significant, morphological explanatory variables in their possible combinations to assess the three selected response variables. The methodology allows estimating the potential energy savings for space heating in urban buildings as a function of their morphologic features and provides a technical basis for the development of a normative aimed at contributing to a greater share of energy and environmental sustainability in the near future.

Keywords: potential energy savings, urban buildings stocks, statistical regression, urban morphology.

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1. INTRODUCTION

Energy use in the built environment has been globally recognized as one of the key issues to be addressed on the path towards a sustainable urban future. [1]

In tempered-cold arid regions with a generous solar resource, adequate building design and technology can contribute to achieve significant economies in the energy demand for space heating in urban buildings. Moreover, the recycling of existing building stocks, implementing greater conservation measures and additional passive solar gain, can provide an important share of the potential energy savings, from the present demand.

The study is focussed on the assessment of the energy recovery potential for space heating in low-density urban building stocks in the city of Mendoza's Metropolitan Area (MMA),

The physical features of the existing buildings, in their morphological aspects, combined with the technological alternatives in their energetic behaviour, are responsible for their environmental and energy performance. Moreover, the maximum possible recycling of existing building stocks is considered essential to minimize environmental impacts throughout human habitat's life cycle.

The results obtained by the use of a graphic-computational model, were first analyzed comparing the single, most significant variables against each other. The need for multivariate analysis became evident due to the number of variables and their possible combinations. The results were finally analyzed using a statistical multiple linear regression model, which allowed identifying and gauging the most significant explanatory variables and their relative weight on each indicator (response variables).

To obtain the targeted maximum savings, it is proposed to upgrade de energy conservation features of the existing buildings and to maximize passive solar

gain for space heating, proceeding, for each indicator, according to the significance of each set of explanatory variables, within policies that favour the greatest possible fossil fuel substitution and the minimum environmental impact. [2].

2. REFERENCE SITUATION

Regional Data:

The region under study is set in mid-western Argentina (Latitude: -32.88, longitude: 68.85, altitude: 827m a.s.l.). It features a dry mesothermal climate, with mild-cold sunny winters, and hot dry summers. MMA, with a population close to a million is endowed with a generous solar resource: (18.06 mj/m² per day, annual average), with 1384 heating DD (base 18 °C). The hours in comfort per year represent 21.53 % while the hours in which heating is needed amount to 70.14 %. That latest figures provide support for the proposal of increased conservation and passive solar use in residential buildings, thereby allowing a significant advance on the path towards environmental and energy sustainability in the future. [3,4].

3. METHODOLOGY

The methodology applied features the following stages:

3.1. Selection of a set of sample units (city-blocks) representative of the universe, for detailed study:

Low-density urban city-blocks of residential use were considered as basic study units.

The 32 case selected sample group should be representative of the various situations the units feature in different combinations: shape and orientation of the urban matrix, homogeneity and heterogeneity of constructions, parcel structure and arboreal presence. The location of the chosen set of study units is mapped in Fig 1.

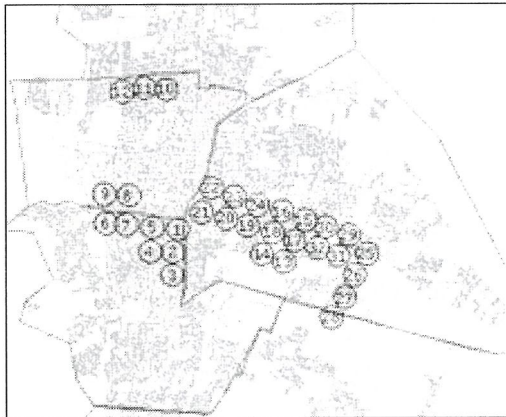


Figure 1: Location of the 32 study units.

3.2. Definition of variables to be analyzed:

Urban variables: Shape of regular city blocks, Orientation of the blocks, Width of the street canyons, City trees (Magnitude, Solar permeability of crowns, Completion).

Building variables: Building morphology (typological homogeneity and heterogeneity), Form Factor (FF) (exposed envelope area/ volume), Soil Occupation Factor (SOF) (built up area on the ground floor / total buildable land area), Total Occupation Factor (TOF) (total built-up area/ total buildable land area) [5].

The areas and volumes calculated correspond to the sum of all buildings in a determined city block, as it would be a single individual structure.

3.3. Determination of insulated areas of complex configuration city blocks.

The insulated areas of north facing walls were calculated using a computational-graphic model developed by the R+D unit [6] By means of axonometric perspectives of the 3D urban insulated volumetric masses, as “seen from the sun” as functions of their azimuth and solar altitude, according to the date and hour. The procedure allows to obtain the areas of north facing walls on the 21st day of each month, from April to August, during the five central hours of the day, i.e. 9:30 a.m. to 2:30 p.m. solar time (period of the

highest radiation intensity, during the heating season) (Fig. 2). Each area was evaluated with and without the insertion of trees. Later the percentages of solar permeability of tree crowns were applied [7] thus determining the real collecting area of north facing walls (the sum of fully insulated areas plus the partially insulated masked by trees). Fig. 2.

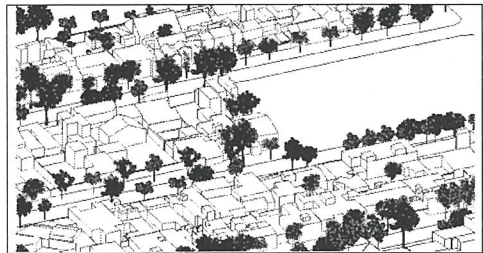


Figure 2: Low density area with trees.

3.4. Estimation of the main indicators of energy behavior in the units under analysis.

The gathered and calculated data on variables allowed, by means of a stationary state thermal balance, to determine the main indicators of the potential solar contribution. The method utilized was the Load Collector Ratio of LANL. [8].

From the results obtained by the models of solar access and conservation calculations, it was possible to determine the potential energy obtainable through recycling, by implementing additional conservation measures and enlarged insulated north facing windows in the units under study.

Two alternatives were calculated:

- The current situation without changes, considering as collectors the existing insulated windows on north facing façades, with the existing conventional building technologies. Within this situation, two possible scenarios were developed, which represent a range between maximum and minimum heat losses. A mean value of both extremes was used as a first approximation.
- The theoretical situation to be reached: (optimized) implementing possible and affordable improvements in energy

conservation technology and maximizing passive solar gain. (Table I).

Table I: Components thermal conductance values of existing and improved buildings.

	PRESENT SITUATION (Mean values)		THEORETICAL SITUATION (optimized)	
	Material	K	Material	K
Roofs	Conc. Slab. =0.08 Expanded polystyrene 0.05	0.6	Wood board =1.8 Expanded polystyrene 0.075	0.4
Exterior walls	Solid brick (0.165) Plastered both faces	2.1	Solid brick (0.265) Exp. polystyrene 0.05 Plastered both faces	0.4
Foundations	Boulder concrete	0.7	Boulder concrete	0.5
Exposed floor slabs	Reinforced concrete slab. 8cm.	3.1	Reinforced concrete slab.8cm. Expanded polystyrene 5cm.	0.6
Windows	Bent plate, single glazing night insulation	4.5	Wood double glazing, night insulation	2.1
Ext. doors	Double wood plank	2.3	Double wood plank	2.3
ARRH	Infiltration	3	Infiltration	1

3.5. Definition and estimation of the chosen indicators:

3.5.1. Mean Insolation Factor (MIF)(%)

Provides a measure of the unmasked potentially collecting north facing walls, calculated as: the ratio of the sum of insulated collecting areas of north facing walls, times the energy received at each considered hour, during a heating season, to the sum of the total areas of the same surfaces, free of all masking, times the sum of the hourly impinging radiation during the considered heating season, as percentage.

$$MIF = \frac{\sum_{m=4}^{08} \sum_{d=1}^{30} \sum_{h=9.30}^{14.30} [Anw - (Amss + (Aps \cdot (1-P))) \cdot R]}{Nm \cdot Nd \cdot Nh \cdot (Anw \cdot R_{max})} \cdot 100 \quad (1)$$

Where:

Anw: Total area of potentially collecting north facing walls, (m2).
Amss: Area masked by solid shading (buildings), (m2).
Amps: Area masked by permeable shading (trees), (m2).
P: Permeability factor, (%).
R(m·h): Hourly radiation on north walls for each month, (Wh/m2).
Nh: Number of hours to which the day is extended to, (n).
Nm: Number of months to which the season is extended to, (n).
(Anw · R) max: Normalization factor
E: Efficiency of conventional heating system, as fraction.

3.5.2. Useful Insolation Factor (UIF)(%).

Expresses the relationship between the useful solar energy available for space

heating impinging on north facing vertical surfaces, to the total energy available impinging on the whole city block, i.e. the normal section to the maximum radiation “prism” on the block’s buildable ground area plus the areas of surrounding streets opposite the incoming radiation, independently of orientation and with the present masking due to buildings and trees, as percentages.

$$UIF = \frac{\sum_{m=4}^{08} \sum_{d=1}^{30} \sum_{h=9.30}^{14.30} A_{iss} \cdot R_{n.s.}}{Nm \cdot Nd \cdot Nh \cdot (Ac_{bns} \cdot R_{n.s. \max})} \cdot 100 \quad (2)$$

Where:

Aiss: Hourly insulated areas of north facing walls as seen from the sun, (m2).
Rns: Hourly mean radiation (direct + diffuse) impinging on insulated north facing walls on surface normal to radiation beam, (Wh/m2).
Nh: Number of hours the day is extended to, (5).
Acbs: Total area of normal section of the radiation prism impinging on the whole city-block, (m2).
Nm.: Number of months the heating season is extended to, (5)
E: Efficiency of the conventional heating system, as fraction.

3.5.3. Potential Energy Savings (PES)(%)

It can be expressed as the ratio between the sum of the energy saved by increased energy conservation measures, plus the energy gained by enlarged insulated north facing windows, (both by recycling of the existing low-density urban building stocks), to the net energy lost by the buildings in their present condition, that is; the gross heat losses less the solar contribution made by existing insulated north facing windows, over a heating season, expressed as percentages.

$$PES = \frac{Q_{cons \text{ renov}} + Q_{solar \text{ renov}}}{Q_{tot \text{ ext}} - Q_{solar \text{ ext}}} \cdot 100 \quad (3)$$

Where:

Q tot. exi: Total annual gross space existing heating load. (Wh/°C)
Q sol. exi: Existing solar energy contribution. (Wh/°C)
Q con.ren: Energy saved by increased conservation, (Wh/°C).
Q sol. ren: Energy gained by enlarged insulated north facing windows as direct gain systems, (Wh/°C).

3.6. Estatistical analysis :

Once the values of the 3 chosen indicators have been calculated, it is necessary to determine which are the variables and their combinations, which will allow maximum potential energy savings by the implementation of the discussed improvements.

The studies on the solar energy potential of urban environments require the analytical consideration of a rather extensive number of variables and their interrelationships. A proper analysis should take into account all the information gathered on the variables.

The objective of the analysis is to explain the potential energy savings of the urban tissues as functions of a group of morphologic explanatory variables. It becomes necessary to consider the use of a statistic multiple linear regression model which, departing from calculated values derived from the graphic-computational model of the explanatory variables, allows a linear interpretation and the construction of a predictive stage for the selected response variables: EIF, UIF and PES.

Multiple linear regression analysis is aimed at predicting the value of a response variable as a linear function of a family of explanatory variables, departing from a sample of representative size whose observations are matricially ordered.

A model was elaborated for each of the chosen indicators, in it, a group of variables explain (linearly) the value of the indicator. The usual steps to best build the linear regression model for the indicator were the following: i. Checking the assumptions of the model. ii. Application of the Box & Cox transformation. iii. Selection of a minimum set of independent explanatory variables to explain the response. iv. Implementation of a step-wise regression method. v. Study of the significance of each independent variable in the selected linear model, the estimated coefficient, its standard error and the value of the t-statistic for the test of its significance and the associated "p-values": < 0.05 significant,

<0.01 very significant and < 0.001 highly significant. [9,10 and 11].

4. RESULTS

The resulting values obtained by both methods, conventional (graphic-computational) and statistic, are close for the 32 cases of the sample set, which leads to confirm the validity of using the statistical model for the assessment of the feasibility of using the solar resource in low-density urban environments. Table II presents the summary of values obtained for the 3 chosen indicators by the conventional and statistical models for the total sample set.

Table II: Complete values for the 3 indicators.

SCEN	MIF		UIF		PES	
N°	STAT	CONV	STAT	CONV	STAT	CONV
1	0.70	0.69	0.19	0.11	0.80	0.78
2	0.73	0.74	0.17	0.12	0.79	0.80
3	0.68	0.70	0.19	0.15	0.81	0.80
4	0.68	0.71	0.15	0.12	0.76	0.79
5	0.67	0.70	0.14	0.08	0.76	0.76
6	0.68	0.65	0.20	0.12	0.78	0.77
7	0.69	0.75	0.19	0.14	0.78	0.78
8	0.68	0.71	0.16	0.12	0.79	0.80
9	0.68	0.66	0.17	0.12	0.79	0.79
10	0.69	0.74	0.13	0.10	0.74	0.75
11	0.73	0.63	0.12	0.11	0.74	0.73
12	0.81	0.78	0.16	0.10	0.77	0.74
13	0.76	0.77	0.12	0.10	0.74	0.75
14	0.74	0.75	0.12	0.10	0.64	0.74
15	0.72	0.73	0.11	0.08	0.74	0.73
16	0.74	0.72	0.12	0.09	0.74	0.74
17	0.69	0.67	0.14	0.15	0.75	0.76
18	0.74	0.76	0.14	0.16	0.75	0.77
19	0.74	0.74	0.07	0.06	0.65	0.66
20	0.72	0.64	0.07	0.05	0.66	0.65
21	0.73	0.73	0.07	0.07	0.65	0.67
22	0.75	0.80	0.09	0.08	0.67	0.69
23	0.70	0.69	0.09	0.05	0.67	0.63
24	0.73	0.71	0.08	0.05	0.66	0.61
25	0.70	0.75	0.11	0.12	0.74	0.75
26	0.69	0.74	0.11	0.11	0.73	0.75
27	0.69	0.68	0.11	0.10	0.74	0.73
28	0.73	0.73	0.11	0.09	0.73	0.74
29	0.50	0.48	0.12	0.07	0.68	0.67
30	0.54	0.50	0.12	0.09	0.68	0.66
31	0.52	0.57	0.12	0.09	0.68	0.71
32	0.94	0.47	0.13	0.09	0.68	0.64
Mean	0.70	0.69	0.13	0.10	0.73	0.73

The values yielded by the "goodness of fit" test for the model's statistical proof, the correlation coefficients to the square which

symbolize the variance explained by the model and the residual standard error are presented in Table III.

Table III: Statistical Model Results for the 3 indicators.

	GOODNESS			EXPLAINED VARIANCE		RESID
	F-Stat.	DF	p-value	Multiple R-Squared	Adj R-Squared	Residual Standard error
MIF	21.14	427	5.4e-08	0.758	0.7221	0.1946
UIF	12.1	625	2.304e06	0.7438	0.6823	0.1924
PES	28.69	625	4.63e10	0.8732	0.8428	0.1075

Tables IV, V and VI. present the values of the estimate coefficients, the standard errors and p-values for each of the 3 respective indicators. In each case, the explaining variables are ordered according to their significance level (those with smaller p-levels first).

Tables IV, V and VI: Significant values for the 3 indicators: MIF, UIF and PES.

	Coefficients:	Estimate	Std. Error	p-value
MIF	(Intercept)	4.196950	0.465424	1.24e-09 ***
	Build. Morph.	0.854698	0.147392	3.60e-06 ***
	Street width	-0.148641	0.029006	2.18e-05 ***
	Tree's Comp	-0.012760	0.003833	0.00253 **
	T O F	-0.472146	0.227477	0.04758 *

	Coefficients:	Estimate	Std. Error	p-value
UIF	(Intercept)	-1.21782	0.60600	0.055385
	Orientation	-0.23076	0.05918	0.000642 ***
	Build.	0.50222	0.15804	0.003924 **
	Morph.	0.73066	0.24727	0.006728 **
	TOF	-0.03933	0.03016	0.204115
	Street width			

	Coefficients:	Estimate	Std. Error	p-value
PES	(Intercept)	0.865001	0.14799	3.19e-06***
	TOF	0.80949	0.111349	8.07e-08 ***
	Orientation	-0.06818	0.018271	0.000895 ***
	SOF	-1.10879	-1.108793	0.005589 **
	Street width	0.018761	0.006975	0.012106 *

The linear models' estimated for each of the 3 chosen indicators results in the following equations:

$$\log\left(\frac{MIF}{1-MIF}\right) = 4.1969 - 0.1486st.wi. - 0.0127treescomp + 0.8547morph - 0.4721TOF \quad (4)$$

$$\log\left(\frac{UIF}{1-UIF}\right) = -1.2178 - 0.2308orien - 0.0393st.wi. - 0.1091Magni - 0.0166Perm + 0.5022morph + 0.7301TOF \quad (5)$$

$$\log\left(\frac{PES}{1-PES}\right) = 0.865001 - 0.068187orien + 0.018761st.wi. - 1.108793SOF + 0.809490TOF \quad (6)$$

For each indicator it is possible to obtain, by antitransforming, a simple equation which can now be used as a practical predictive tool of the indicators' values, without going through the complex procedure of solar incidence determination by the graphic model. The corresponding equations for the 3 indicators are presented below:

$$MIF = \frac{\left[\exp(4.1969 - 0.1486st.wi. - 0.0127comp + 0.8547B.Morph + 0.4721TOF) \right]}{\left[1 + \exp(4.1969 - 0.1486st.wi. - 0.0127comp + 0.8547B.Morph + 0.4721TOF) \right]} \quad (7)$$

$$UIF = \frac{\left[\exp(-1.218 - 0.23lorie - 0.039st.wi. - 0.109magn - 0.017perm + 0.502B.Morph + 0.731TOF) \right]}{\left[1 + \exp(-1.218 - 0.23lorie - 0.039st.wi. - 0.109magn - 0.017perm + 0.502B.Morph + 0.731TOF) \right]} \quad (8)$$

$$PES = \frac{\left[\exp(0.865001 - 0.068187orie + 0.018761st.wi. - 1.108793SOF + 0.809490TOF) \right]}{\left[1 + \exp(0.865001 - 0.068187orie + 0.018761st.wi. - 1.108793SOF + 0.809490TOF) \right]} \quad (9)$$

The ensuing verification and validation of the predictive tool on 3 cases outside the main sample set, yielded, as an average a confidence level of 99 %.

5. CONCLUSIONS

From the viewpoint of the energy and urban planning levels, the PES indicator is obviously the most significant and the one that deserves greater consideration. MIF and UIF are to be addressed mainly at the design level and the local scale. Concentrating now on the PES indicator, the results of the conventional assessment are conclusively indicating a significant

potential for energy savings from present requirements of non-renewable energy for space heating in urban buildings, in low-density areas of MMA. The PES values yielded range from 61 to 80 % and an overall mean value of 73 % for the complete sample set. The correlations between the results of the conventional model (graphic-computational) and the statistical model were performed finding an explained variance of 71 %.

The contribution of the statistical assessment, proven its high level of agreement with the conventional evaluation, is centred on the determination of the most significant explanatory variables on the response variables and the production of a simple predictive tool, useful to support design an urban planning strategies aiming at energy and environmental sustainability.

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