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A GIS-based statistical approach to prioritize the retrofit of housing stocks at the urban scale

基于地理信息系统的统计方法用于城市规模住房存量改造的优先等级处理

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Abstract - **Cities are responsible for about 70% of the overall primary energy consumption in Europe and play a major role in addressing carbon mitigation. In this respect, the housing sector has been identified as a key sector for its high energy savings potential achievable by implementing retrofit measures. However, a detailed characterization of the housing energy consumption profile and spatial distribution is needed to properly assess the energy saving potential at the urban scale and further support sustainable urban planning and energy policies.**

This study focused on a statistical approach based on Geographical Information Systems (GIS) developed to identify the energy consumption profile of urban housing stocks, the energy savings potential achievable by implementing retrofit measures and their respective spatial distribution across one entire city. The final energy consumption of individual dwellings is predicted by running a multiple linear regression model based on measured energy consumption available at aggregated level (post-code area level) and GIS data about characteristics of buildings and household. Energy savings potential and cost-effectiveness of standard retrofit measures are subsequently calculated and results are finally displayed as maps for decision support in sustainable urban planning. The methodology was applied to the exemplary housing stock of Rotterdam city, consisting of almost 300,000 units.

Relevant results are provided to prioritize retrofit measures implementation according to energy savings potential and cost-effectiveness. Different types of maps can be produced to show energy consumption and energy saving potential patterns across the city. The methodology is generically applicable to other contexts and provides an effective tool for decision support in carbon mitigation policies of housing stocks at the urban scale.

Keywords – **Building stock; Energy savings; Costs; Sustainable urban planning.**

I. INTRODUCTION

Cities play a major role in addressing carbon mitigation as they are responsible for about 70% of the overall primary energy consumption in Europe [1]. A significant part of the energy consumption and greenhouse gases emission of cities is attributable to the building sector. As a consequence, the European Directive 2012/27/EU[2] required the Member States a long term strategy for mobilizing investment in this sector. In particular, the housing sector has been identified as one of those with the highest energy savings potential achievable through the implementation of retrofit measure. However, a detailed characterization of the housing energy consumption profile and spatial distribution is needed to properly assess the energy savings potential at the urban scale and further support sustainable urban planning and energy policies. Several types of bottom-up housing stock models have been developed to this end [3]. Statistical models use historical data to attribute final energy consumption to single or groups of buildings using a range of statistical techniques. Even though statistical models are limited in predicting the impact of new technologies, they can efficiently be used to estimate the actual energy consumption profile of the building stock including the effect of the real state of renovation and behavior of occupants. A few statistical models have been already developed for the housing sector, however there is a lack of studies at the urban scale and taking into account the spatial distribution of energy consumption [4].

The objective of this study was to identify the energy savings and CO2 reduction potential of retrofit measures for urban housing stocks in order to prioritize their implementation across one entire city also using cost-effectiveness criteria. A statistical approach based on Geographical Information Systems (GIS) was developed for this scope. The final energy consumption of individual dwellings was predicted by running a multiple linear regression model based on measured energy consumption available at aggregated level (post-code area level) and GIS data about characteristics of buildings and households. Energy savings potential and cost-effectiveness of standard retrofit measures were subsequently computed using benchmark values and results were finally displayed as maps for decision support in sustainable urban planning.

The methodology was developed as part of the European INTERREG IVB NEW project MUSIC [5] to be implemented into the web-based integrated decision support platform iGUESS [6].

II. CASE STUDY

The housing stock of Rotterdam city, counting 297,312 dwellings in 2012, was taken as a case study. Six typologies of dwellings can be identified, distributed into houses (detached, semi-detached, row-houses) and apartments (maisonette, “galerij” flats, “portiek” flats). Houses account for 24% of the total number of dwellings in Rotterdam with a predominance of row-houses (16%) and a minor share of semi-detached (7%) and detached houses (1%). Apartments represent about 76% of the stock divided into maisonettes (22%), galerij flats (19%) and portiek flats (35%). About 51% of the dwellings were built before 1965, 10% in the period 1965-74, 23% in 1975-1991 and 13% in 1991-2005.

The main energy carrier for space heating, domestic hot water and hob cooking is natural gas, while about 17% of dwellings are connected to the urban heating network. Electricity is mainly used for lighting and appliances and partly for domestic hot water.

Data about dwellings and households were extracted from the GIS address database of the Municipality, including information about floor surface, type of dwelling and period of construction, number of occupants. Measured natural gas consumption are available on a yearly basis at the post-code area level. National building libraries and standards [7,8] were used to apportion the total energy consumption into different end-uses and to estimate the energy saving potential and investment costs for standard retrofit packages.

III. METHODOLOGY

A bottom-up statistical approach based on GIS was developed at the city scale to predict the final energy consumption of the housing stock [4]. Multiple linear regression is used to disaggregate measured natural gas consumption values available at post-code area level to single dwellings depending on building and household features. The equation at the basis of the model for gas is Eq (1):

$$y = \beta_0 + x_{floor}\,\beta_{floor} + \Sigma_i\, x_{type,i}\,\beta_{type,i} + \varepsilon \qquad (1)$$

where the dependent variable y represents measured yearly average gas consumption per dwelling at post-code level, the independent variable x_{floor} the average floor surface of dwellings, $x_{type,i}$ the percentage of dwellings per type and period of construction (26 combinations) in the post-code, β_0, β_{floor}, $\beta_{type,i}$ the regression coefficients to be estimated commonly by ordinary least squares technique and ε a random error term. The residuals were carefully analyzed and their spatial distribution displayed at post-code level so to identify areas with higher consumption deviation and detect possible spatial patterns. The software QGIS [9] was used for this scope.

The total natural gas consumption was apportioned into different end uses and the energy savings potential and costs of standard retrofit measures were calculated based on national benchmark values and standards [7,8]. Standard retrofit packages include isolation of external walls, roof and ground floor, windows replacement and boiler replacement according to Dutch regulations (Table 1).

An index to evaluate the cost-effectiveness of retrofit measures $C_{en.sav}$ *(€ / kWh a)* was defined according to Eq (2):

$$C_{en.sav} = I_{retr} / E_{sav} \qquad (2)$$

where I_{retr} *(€)* is the investment cost of the standard retrofit measure package and E_{sav} *(kWh)* is the yearly energy savings potential. Such index is suitable to prioritize the implementation of retrofit measures for residential buildings across the city.

TABLE 1, STANDARD RETROFIT PACKAGES FOR THE BUILDING ENVELOPE IN THE NETHERLANDS (ADAPTED FROM [7]).

Retrofit package	U-value *(kWh/m^2K)*	Rc-value *(m^2K/kWh)*
External wall insulation	0.36	2.53
Roof insulation	0.36	2.53
Ground floor insulation	0.36	2.53
Double Glazing LowE - *HR^{++}*	1.80	-

Energy consumption and energy savings predicted for single dwellings were aggregated across the city at the block level and their distribution was spatially analyzed using GIS. The block level was selected as the *target level* where to show information useful for decision support in urban planning as this level gives sufficient detail in results and at the same time keeps sensitive data protected (e.g. information for single buildings). Maps were generated at the block level for the total primary energy consumption for space heating and domestic hot water in the current state, the total energy savings potential achievable through standard retrofit measures and the average cost of energy savings.

IV. RESULTS AND DISCUSSION

The multiple linear regression model for the natural gas consumption of the Rotterdam housing stock was found to be significant with coefficients of determination $R^2 = 0.734$ [4]. The model results demonstrated a good accuracy in the prediction. Fig. 1 shows the distribution of predicted against measured average gas consumption for the post-code areas used to fit the model. Deviation of natural gas consumption is in the range of ±20% in 82% of the cases.

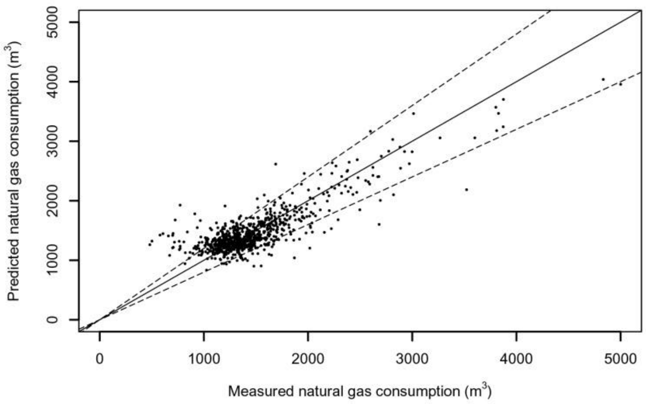

Fig. 1, Average natural gas consumption per dwelling at post-code level: predicted against measured values. The dotted lines contain cases within ±20% error. Adapted from [4].

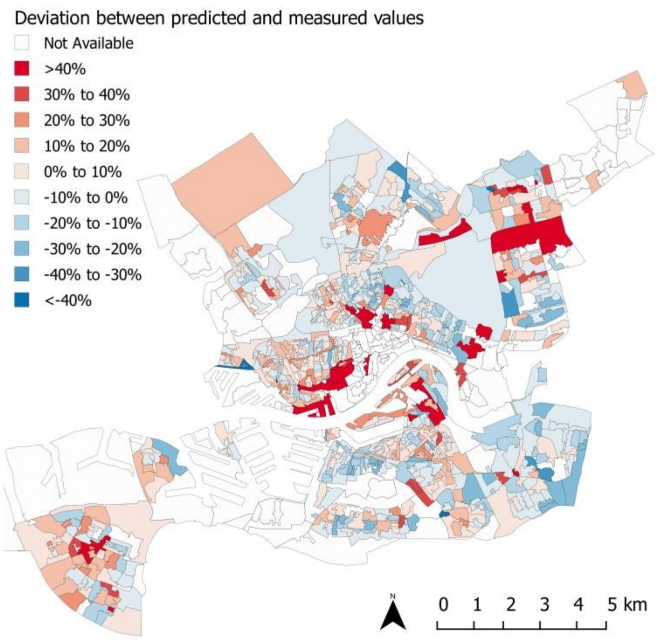

Fig.2, Map of deviation between predicted and measured yearly average natural gas consumption at post-code level in Rotterdam.

The residuals are further displayed on a map at the post-code level to visualize their spatial distribution (Fig.2). Deviations in consumption tend to concentrate in various parts of the city, indicating the possible presence of effects at local scale. Specific configuration of buildings, household composition, income level and other social factors might determine this effect and must be further analyzed in a future step. The largest deviations were detected for few small areas where only one building with special characteristics is present, such as a big residential complex. Overall, the comparison between fitted and measured values demonstrated that the prediction given by the model is accurate across the city.

The estimated regression coefficients were used to predict the energy consumption of dwellings across the city. Fig. 3 shows the distribution of natural gas consumption predicted by type of dwelling for the whole stock.

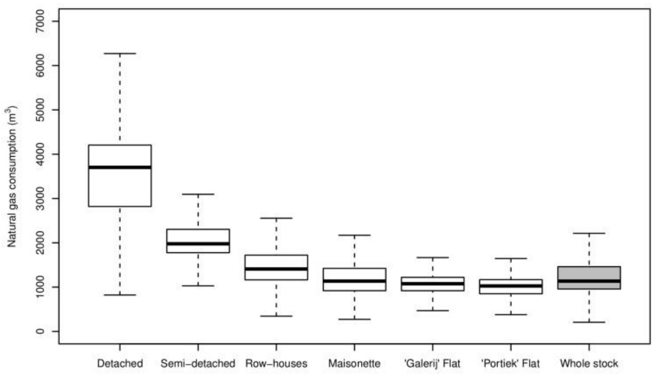

Fig. 3, Distribution of predicted yearly natural gas consumption of dwellings by type for the whole housing stock of Rotterdam.

Gas consumptions are higher for houses than for apartments due to larger floor surface and heated volume. In addition, less compact dwelling types such as detached and semi-detached are more energy consuming because of their relatively large envelope surface area compared to their volume, resulting in higher heat losses.

TABLE 2, ENERGY SAVINGS POTENTIAL FOR SPACE HEATING AND DOMESTIC HOT WATER BY HOUSING TYPE AND PERIOD OF CONSTRUCTION (ADAPTED FROM [4]).

Energy savings potential Period of construction	Houses	Apartments
<1946	65 - 68 %	41 - 70%
1946-1964	58 - 68 %	41 - 70%
1965-1974	48 - 61 %	40 - 49%
1975-1991	33 - 40%	24 - 31%
1992-2005	5 - 13%	4 - 13%

The estimated energy savings potential for space heating and domestic hot water associated to the retrofit of residential buildings is reported in Table 2 by dwelling type and period of construction. The potential is higher for older buildings and progressively decreases for more recent ones. The typology has a relative influence on results depending on both different envelope thermal properties and geometry. For instance, insulating buildings with a less compact shape can lead to major energy savings because of the higher influence of the heat losses by transmission on the energy demand.

The values of energy consumption and energy savings potential, calculated at dwelling level, were aggregated at the block level and displayed as spatial maps for the entire city of Rotterdam (Figs. 4-5).

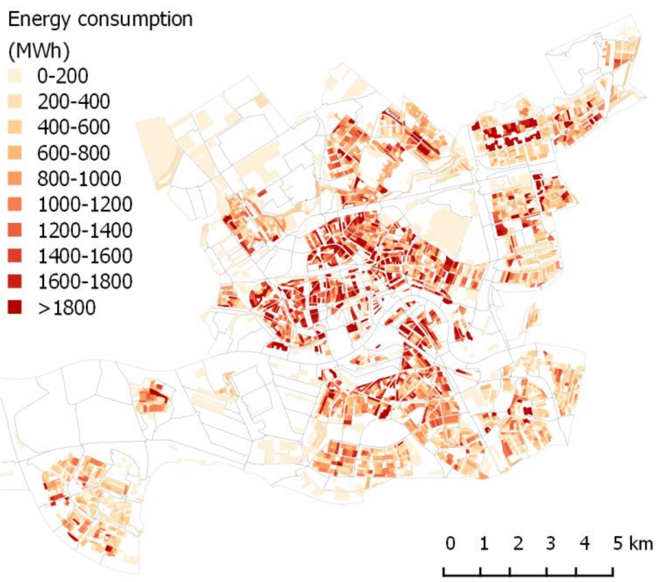

Fig.4, Map of primary energy consumption at block level for space heating and domestic hot water of dwellings across Rotterdam.

Fig. 4 displays maps of primary energy consumption for space heating and domestic hot water of dwellings across the whole city. Higher energy consumption is registered for the city center and adjacent areas characterized by high density and the presence of older flats and row-houses. In contrast, the city suburbs have total lower energy consumption due to a lower density, despite the presence of detached and semi-detached houses more energy consuming.

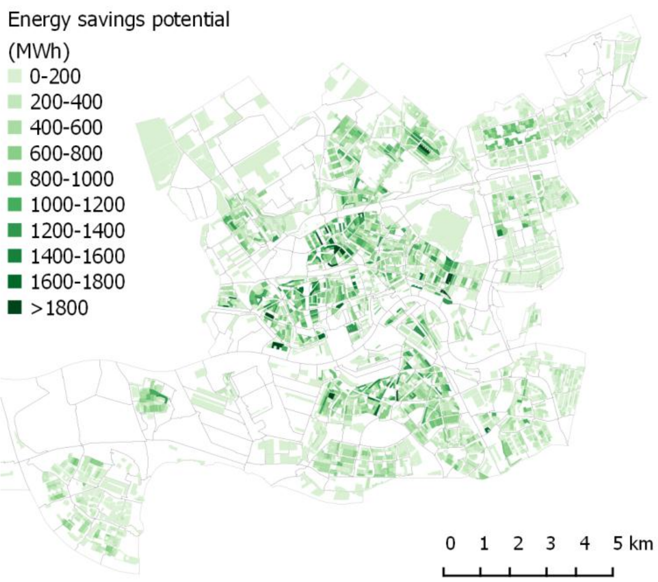

Fig.5, Map of energy savings potential at the block level for space heating and domestic hot water of dwellings across Rotterdam.

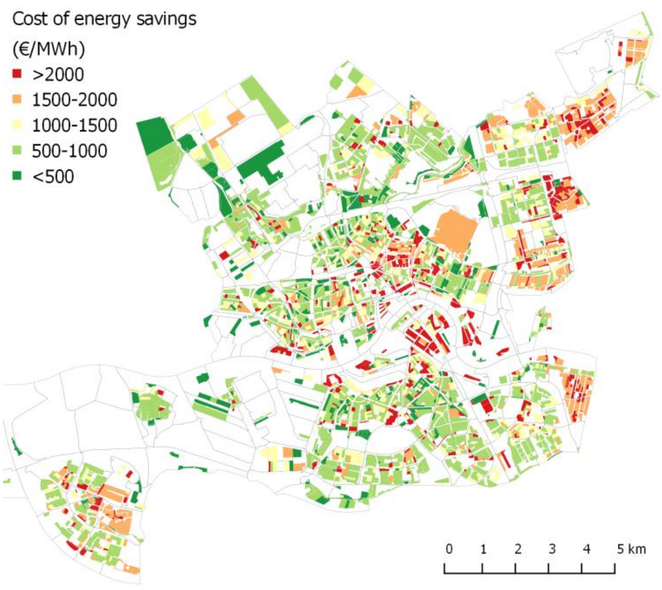

Fig. 6, Map of cost of yearly energy savings at the block level for space heating and domestic hot water of dwellings across Rotterdam.

The map in Fig. 5 shows the energy savings potential for combined space heating and domestic hot water achievable through the implementation of typical retrofit measures for buildings. The map is suitable to identify across the city areas where the retrofit of residential buildings is more promising in terms of energy savings. These areas are characterized by a dense urban tissue and the predominance of old buildings.

A map was drawn at the block level to show the cost-effectiveness of retrofit measures across the city (Fig. 6). The cost of energy savings depends on the type and period of construction of dwellings present in a specific area. Lower cost values indicate higher cost-effectiveness of retrofitting. The cost of energy savings decreases for older buildings, indicating an higher cost-effectiveness of retrofit measures (Table 3). The areas of Rotterdam where the distributed retrofit is expected to be more cost-effective are mainly located in the belt around the city center and in some of the suburbs where the presence of older buildings is larger. However, by comparison of this map (Fig. 6) with the energy savings potential map (Fig. 5) it emerges that not every area where the retrofit is more cost-effective has a large energy savings potential. This depends mainly on the urban density, for instance areas in the outskirts with old detached houses and low density tissue, have high cost-effectiveness values for retrofit but low energy savings potential. The two maps can be used in combination to support decision and prioritization of retrofit measures across the city.

TABLE 3, ENERGY SAVINGS POTENTIAL, CO_2 REDUCTION POTENTIAL AND MEAN COST OF ENERGY SAVINGS IMPLEMENTING STANDARD RETROFIT MEASURES FOR THE HOUSING STOCK OF ROTTERDAM.

Dwelling category	Tot. energy savings potential *(GWh/a)*	Tot. CO_2 reduction potential *(kton/a)*	Mean cost of energy savings *(€/MWh /a)*
Period of construction			
<1946	853.0	162.2	657
1946-1964	344.9	68.0	867
1965-1974	164.2	32.1	939
1975-1991	218.3	50.8	2025
1992-2005	39.3	8.59	2284
Type of dwelling			
Houses	572.4	109.8	1134
Apartments	1046.6	211.9	1268
Whole stock	**1619.7**	**321.7**	**1231**

Results of the energy savings potential and CO2 emission reduction computation for the whole housing stock of Rotterdam are reported in Table 3 distributed by period of construction and type of dwelling. The highest potential can be provided by buildings constructed before 1964 for a yearly saving of *1197,9 GWh*, corresponding to the 74% of the total. Considering the type of dwelling, apartments have a yearly potential of *1046.6 GWh*, almost 65% of the total. The total energy savings potential for the whole housing stock amounts to *1619.7 GWh* per year while the CO2 reduction potential to *321.7 kton* per year.

V. Conclusions

A GIS-based statistical approach was developed to analyze the energy consumption of housing stocks at the urban scale and to prioritize the implementation of retrofit measures. The methodology was tested on the residential stock of Rotterdam city but can be generically applied to other contexts.

The linear regression model made it possible to disaggregate natural gas consumption data available at post-code area level accurately enough to predict energy consumption of single dwellings across the entire city. A preliminary evaluation of the spatial distribution of errors from the statistical analysis was carried out to detect the presence of possible spatial patterns and will be object of further spatial analysis. Maps of the energy consumption for space heating and domestic hot water in the current state, energy savings potential given by standard retrofit measures and cost of energy savings were produced for the whole housing stock.

Results for Rotterdam City demonstrated that the energy savings and CO_2 reduction potential achievable by the retrofit of the existing housing stock are significantly high, respectively *1619.7 GWh* and *321.7 kton CO_2*. Retrofitting is particularly convenient and effective for the portion of the housing stock built before 1965 and for apartment blocks.

This approach can constitute a valid support to promote and prioritize the retrofit of the housing stock at the city scale based on energy savings, CO2 emissions and costs. The results generated for the housing stock can be further used as support for planning renewable energy local production or urban heating networks.

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