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A parametric sensitivity analysis of the influence of urban form on domestic energy consumption for heating and cooling in a Mediterranean city

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ABSTRACT

The study presents the results of a parametric analysis of the impact of urban form on domestic energy consumption for heating and cooling. Three urban typologies, the pavilion, the slab and the perimeter urban block are examined using the dynamic building energy simulation software EnergyPlus. The simulation results are processed through a sensitivity analysis using the 'standardised rank regression coefficients' technique to determine the relative influence of the examined parameters on energy consumption. The study focuses on the Mediterranean city of Thessaloniki which has both heating and cooling requirements. The results support the argument that there is a synergy between the strategies of high urban compactness and passive solar design and that this synergy can be achieved at different urban densities.

1. Introduction

In a rapidly urbanising world, the relationship between urban form, climate and residential energy consumption remains a vague topic for many planning and design professionals (LSE Cities, 2011). Reviews of the relevant literature (Ko, 2013; Vartholomaios, 2015a) reveal two important energy-efficient urban design strategies. On one hand, the need to reduce heating loads by maximising the passive use of the sun points towards loose urban forms characterised by southern orientations and adherence to minimum distances (DeKay & Brown, 2014; Erley & Jaffe, 1997; Knowles, 2006; Montavon, 2010; Olgyay & Olgyay, 1963). On the other, the argument of higher urban densities that minimise undesirable building heat losses or gains, suggests compact urban blocks which are often found in historic European city centres (Curreli & Roura, 2010; Goulding, Lewis, & Steemers, 1992; LSE Cities, 2011; Rode, Keim, Robazza, Viejo, & Schofield, 2014; Steemers, 2003; Strømann-Andersen, 2012; Taleghani, Tenpierik, Van Den Dobbelsteen, & De Dear, 2013; Yannas, 1994). While a few decades ago these design strategies might be considered incompatible (e.g. Owens, 1986), more recent studies (Cheng, Steemers, Montavon, & Compagnon, 2006; Compagnon, 2004; Knowles, 2006; Okeil, 2010; Steemers, 2003; Strømann-Andersen & Sattrup, 2011; Vartholomaios, 2015b) have demonstrated that the development of compact urban forms with high passive solar potential is feasible.

Although the multifaceted relationship of urban form and energy use is generally acknowledged and emphasised by design guidebooks (e.g. DeKay & Brown, 2014; Givoni, 1998; Littlefair et al., 2000), the published studies that examine aspects of this relationship are relatively few (Ko, 2013). A number of parametric studies often focus on specific environmental factors, such as building insolation and daylighting, however, their impact on building energy use is not always quantified (Capeluto & Shaviv, 1997; Cheng et al., 2006; Compagnon, 2004; Kämpf & Robinson, 2010; Martins et al., 2016; Okeil, 2010; Oliveira Panão, Gonçalves, & Ferrão, 2008; Ratti & Morello, 2005; Stasinopoulos, 2011; Van Esch, Looman, & De Bruin-Hordijk, 2012; Vartholomaios, 2015b). Similarly, parametric studies tend to focus on a particular representation of urban geometry, often in the form of an array of buildings (Cheng et al., 2006; Martins, Adolphe, & Bastos, 2014; Oliveira Panão et al., 2008; Stasinopoulos, 2011), urban canyons (Andreou, 2014; Strømann-Andersen & Sattrup, 2011; Van Esch et al., 2012; Vartholomaios, 2015b) or urban blocks (Kämpf & Robinson, 2010; Morello, Gori, Balocco, & Ratti, 2009; Vermeulen, Kämpf, & Beckers, 2013). Yet, parametric studies that compare the energy performance of urban

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blocks with other urban typologies are rare and often do not consider the effect of changes in important morphological parameters, such as orientation (LSE Cities, 2011; Rode et al., 2014), street width (Quan, Economou, Grasl, & Yang, 2014) or urban block shape (Taleghani et al., 2013; Tereci, Ozkan, & Eicker, 2013) on energy consumption.

Hence, it can be observed that, regarding the relationship of urban form and residential energy use, the existing literature leaves a number of questions open or partially answered, especially regarding the performance of the urban block in relation to other typologies. Can certain urban forms achieve low energy consumptions in residential buildings through a synergy of the two aforementioned design strategies? What are the common qualities of these forms in terms of geometry and urban density? Should a particular urban typology be preferred over the rest?

The present study seeks to address these questions of high practical value by conducting a parametric analysis of the influence of key descriptors of urban form on domestic energy consumption for heating and cooling. The novelty of the method presented in this study lies in the application of a sensitivity analysis (SA) technique called 'standardised rank regression coefficient' on a parametric study of three urban typologies (pavilion, slab and perimeter urban block) using a dynamic building energy model. The use of SA in this study enables the exploration of the co-influence of urban form parameters on the energy consumption of typical apartments. The study focuses on the city of Thessaloniki in Greece, which has a Mediterranean climate with both heating and cooling needs. Parametric simulations are conducted using Designbuilder 4.6 which utilises the EnergyPlus 8.3 simulation engine.

2. Background

The main goal of parametric energy studies at the urban scale is to estimate the relative influence of parameters, usually of geometrical nature, on energy use. A basic constraint is the number of parametric combinations that can grow exponentially, a problem also known as the 'curse of dimensionality' (Shultz et al., 2011). Optimisation algorithms have been employed to deal with this issue (Camporeale, 2013; Kämpf & Robinson, 2010; Martins et al., 2014; Montavon, 2010; Oliveira Panão et al., 2008; Vermeulen et al., 2013), however they are more suitable in exploring design alternatives rather than assessing the sensitivity of energy use to changes across the examined parametric space.

The use of urban and building typologies and the standardisation of the examined parameters is an integral aspect of parametric studies. For example, some authors (Calcerano & Martinelli, 2016; Quan et al., 2014; Ratti, Raydan, & Steemers, 2003; Tereci et al., 2013) refer to the basic urban forms analysed by Martin and March (1972), while others employ more recent methods of typological classification, such as the Spacematrix (Rode et al., 2014). The abstractions of forms, uses and construction characteristics reduce the number of parametric combinations to manageable levels and allow the simulation results to be easily interpreted by designers (Taleghani et al., 2013).

Typologies are archetypal, considering that their form is generic. Consequently, their form can be described with more precision using additional geometrical parameters. The selection of the examined parameters depends on the research aim of each study. A simple way to describe the spatial configuration of built volume is to use two basic parameters, the 'envelope surface-to-volume' (S/V) ratio and the 'open space width-to-building height' (W/H) ratio (Ko, 2013). These ratios express building compactness and the relation of buildings to the surrounding open spaces respectively. Openness can also be described by the more sophisticated 'sky exposure' (Zhang et al., 2012) and 'sky view' (Oke, 1987) factors. The S/V and W/H ratios provide unique physical interpretations of the energy performance of urban form. Compact urban configurations with low S/V ratios reduce heat exchanges with the environment, while open spaces with higher W/H ratios generally admit more solar radiation (DeKay & Brown, 2014; Goulding et al., 1992; Ko, 2013; LSE Cities, 2011). The impact of W/H ratio on heating and cooling loads largely depends on the local climate, building orientation, local shading and distribution of openings and other solar collecting surfaces (DeKay & Brown, 2014; Ko, 2013). In the case of urban blocks, orientation becomes less absolute (Gupta, 1984) and an indicator of shape, such as block elongation, may also be required to assess their performance. Block elongation is used in this study as a shape indicator, since DeKay and Brown (2014) have suggested that urban blocks in hot-arid and temperate climates should be elongated along the East-West (E-W) axis to maximise southern building orientation. According to the same authors, streets running E-W should be wide enough to permit winter sun, while North-South (N-S) streets should be relatively narrow to increase summer self-shading of building volumes.

Other descriptors of urban form have been used in previous parametric energy studies, such as the 'passive to non-passive zones' ratio (Ratti, Baker, & Steemers, 2005), the 'insolation-to-total floor area' ratio (Stasinopoulos, 2011) and the 'south wall area-to-building volume' ratio (Albatici & Passerini, 2011). Adolphe (2001) has proposed several morphological indicators of environmental performance that can be calculated using the Morphologic software. A number of studies have employed urban form descriptors that are commonly used in urban planning practice, such as building height, plot ratio and site coverage (Cheng et al., 2006; LSE Cities, 2011; Martins et al., 2014; Strømann-Andersen & Sattrup, 2011; Tereci et al., 2013). Finally, some authors have focused on more detailed qualities of urban form such as building shape (Hachem, Fazio, & Athienitis, 2013), roof type (Van Esch et al., 2012), distribution of openings (Tereci et al., 2013) and position of vegetation (Calcerano & Martinelli, 2016).

Another important aspect of parametric energy studies at the urban scale is the method of energy use calculation. Methods range from the statistical analysis of existing building data and simple heat balance calculations to dynamic thermal simulations. An example of the first method is the Energy and Environmental Prediction (EEP) model (Jones, Lannon, & Williams, 2001) that is GIS-based and relies on building type classification. The use of simplified calculations of heat energy flows offers the advantage of fast modelling over large urban sites. This approach is employed by CitySim software (Kämpf & Robinson, 2007; Robinson et al., 2009), by the 'LT Urban' method (Baker & Steemers, 1992; Ratti, Robinson, Baker, & Steemers, 2000) and by several urban energy balance models used in climatological studies (Grimmond et al., 2010). Dynamic simulation software, such as IES- VE, EnergyPlus and TRNSYS, generally offer the greatest accuracy in modelling building energy consumption. While not typically suitable for simulating large urban sites, these programs have been successfully used in several small-scale studies of urban form (Chung, Kiang, Choo, & Chun, 2011; Pisello, Taylor, Xu, & Cotana, 2012; Strømann-Andersen & Sattrup, 2011; Taleghani et al., 2013; Van Esch et al., 2012).

The simulation results can be processed using SA techniques to estimate the relative influence and therefore importance of different design parameters on building energy performance (Tian, 2013). According to a review by Nguyen and Reiter (2015) SA techniques range from simple graphical or 'one-at-a-time' methods to more complex 'statistical' methods that allow the quantification of the combined influence of multiple inputs on the outputs of a studied system. Statistical methods include linear regression analyses, analysis of variance (ANOVA), the Fourier amplitude sensitivity test (FAST), Sobol's method, Spearman coefficient, the standardized