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Cities and Energy: Urban Morphology and Residential Heat Energy Demand

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Cities and Energy: Urban Morphology and Residential Heat Energy Demand

Abstract. This paper aims to better understand the theoretical heat-energy demand of different types of urban form at a scale of 500 by 500 metres. The empirical basis of this study includes samples of dominant residential building typologies identified for Paris, London, Berlin and Istanbul. In addition, archetypal idealised samples were created for each type through an analysis of their built form parameters and removal of unwanted 'invasive' morphologies. The digital elevation models of these real and idealised samples were run through a simulation that modelled solar gains and building surface energy losses to estimate heat-energy demand. In addition to investigating the effect of macro scale morphological parameters, micro scale design parameters, such as U-values and glazing ratios, as well as climatic effects were analysed. The theoretical results of this study suggest that urban morphology induced heat energy efficiency is significant and can lead to a difference in heat energy demand up to a factor of 6. Compact and tall building types were found to have the greatest heat energy efficiency at the neighbourhood scale while detached housing was found to have the lowest.

Key words: Urban form, building energy consumption; digital elevation models; urban morphology; heat energy

1 Introduction

Buildings concentrate a large proportion of global energy demand. In the developed world, approximately 40 per cent of energy end-use takes place in buildings, while in the developing world the figure is still significant at 20 per cent (Pérez-Lombard et al., 2008). In 2004, this resulted in global emissions of 8.6 GtCO2e (Levine et al., 2007) or approximately 33 per cent of all energy related greenhouse gas emissions and 17.6 per cent of all anthropogenic greenhouse gas emissions (Rogner et al., 2007). Within some cities, the dominance of buildings in relation to energy demand is even more pronounced. In the case of London, the energy used in buildings amounts to almost 70 per cent of the city's total energy demand (UN-Habitat, 2008), with a similar share of carbon emissions (Mayor of London, 2010). In Berlin, building energy use is slightly lower at about 56 per cent, but still far exceeds transport and industry related energy demand (UN-Habitat, 2008). So evidently, the building sector is the most significant contributor to carbon emissions in the global north, but at the same time has also been highlighted as a sector with great opportunities for significant improvement.

This paper focuses on theoretical heat energy efficiencies created by the spatial configuration of cities. Of all energy used in buildings, energy for space heating produces the greatest demand. In Europe, approximately 70 per cent of energy use in residential buildings is heating related (WBCSD, 2009) while a recent more detailed study for New York City identified a range between 55 to 65 per cent of total energy consumption in residential buildings as space heating related (Howard et al., 2012). In principle, three areas of intervention have the capacity to play an important role in reducing heat-energy demand. These include behavioural adjustments, technological advancement and design considerations. For the overall energy consumption in non-domestic buildings, Baker and Steemers (2000) suggest that these three factors together might explain an energy demand variation of a factor of 10 (2, 2 and 2.5 respectively). To fully explain the up to 20-fold difference observed for energy demand of buildings, Ratti et al (2005a) question whether urban geometry might be the missing factor 2. This study addresses this question by focusing exclusively on theoretical heat-energy demand (excluding space cooling and air conditioning) related to design issues at their most fundamental level: building design and urban form.

Our research takes the established discourse on heat-energy demand and building typologies to a larger scale, so allowing for an exploration of trade-offs and scaling effects at the neighbourhood level that have to date been neglected by the existing literature. The following underlying research hypothesis served as the basis for our investigation:

The basic configuration of residential buildings in cities (urban morphology) at the neighbourhood scale significantly impacts on heat-energy demand with more compact urban morphologies displaying far greater heat-energy efficiency than suburban and modern building configurations such as residential towers and slab housing.

To investigate this hypothesis, the archetypal morphologies of four major European cities are analysed and categorised to create generic idealised morphology types. These morphology types are then modelled in order to compare their thermal performance as a result of passive solar heat gains and overall heat losses. Alongside this overall research framework, the following questions are addressed:

- What is the relationship between the most basic spatial characteristics such as gross floor area ratio (floor space index), surface-to-volume ratio and surface coverage for the selected samples?
- What is the average theoretical annual heat energy demand per square metre for each of the real and the idealised morphology samples?
- What patterns emerge regarding the heat energy demand of similar building typologies across the four different cities?
- What are the variations of heat-energy demand within similar, and between different categories of urban morphologies?

This work is intended to provide a basis for future research on design-induced heat energy performance of buildings at the neighbourhood scale. In addition, the categorisation of urban morphology types aims to contribute to an evolving metric for building typologies.

2 State of Research

2.1 Pioneering work at the macro and micro level

At the macro scale, the relationship between urban form and energy consumption was initially investigated through large scale observable parameters such as density and shape. Steadman (1979) was among the first to theorise the energy implications of large scale urban form. His conclusions were that high-density growth along linear transport infrastructure would be more efficient than centralised dense growth. Increasing the possibility of passive solar gains, natural lighting, ventilation and local food production were seen as the benefits of this kind of urban footprint. These early findings formed the basis for many future studies on the effects of morphology on energy demand, although more recent literature is less certain of its conclusions. Some highlight the negative impacts of density on natural light, solar gain and ventilation as important trade-off factors (Hui, 2001), and the possibility that the relationship between density and efficiency may not be causal (Lariviere and Lafrance, 1999; Steemers, 2003) while others generally subscribe to the concept of ‘density equals efficiency’ (Holden, 2004; Mindali, 2004).

At the micro scale, at the level of the individual building, energy demand analysis was initially based on geometric approximations of building form and basic scientific principles (Olgyay and Olgyay, 1963) and supported by experimental results (Olgyay, 1967). Martin (1967; 1972), March and Trace (1969) investigated the relationships between surface coverage, building height, building depth and density to understand the equivalent levels of day lighting. The desire to practically apply the learning from such work led Baker and Steemers to develop the ‘lighting and thermal’ (LT) method (Baker and Steemers, 1995;

Baker and Steemers, 1996; Baker and Steemers, 2000; Roaf and Hancock, 1992). The LT method involves differentiating between passive and non-passive zones within the building. Passive zones are defined as those with a depth (distance from an exterior wall) normally twice the floor to ceiling height, therefore having potential access to passive lighting, heating, cooling and ventilation. Active zones are all those which are unable to take advantage of passive systems and require the 'active' use of energy to provide lighting, heating, cooling and ventilation. The overriding message using this method was to 'avoid deep plan' buildings (Baker and Steemers, 1996). With a few notable exceptions (Knowles, 1974), research was generally divided between the macro and micro scales of understanding; those at the city level, and those at building level.

2.2 New computer-based analysis

Computer-assisted research tools had a profound impact on the field of urban morphological research. More complex geometries could be explored and calculations could be rapidly repeated for many buildings in order to expand the analysis to the neighbourhood scale. Webster (1996) developed image texture analysis techniques for urban morphology research, showing that urban density data could be extracted from satellite imagery. Richens (1997) took this work still further by incorporating image processing techniques and a digital elevation model (DEM), a tool previously used by geographers to overlay three dimensional topographical features onto two dimensional images, producing something akin to a three-dimensional figure ground drawing and allowing the automation of the previously manual LT method (Baker and Steemers, 2000).

At the level of the individual building, Steadman et al. (2000) conducted a comprehensive categorisation of non-domestic building stock (NDBS) with the primary aim of creating a database of building form to be used for energy analysis. From a survey of 3,350 buildings in four English towns, classification criteria focused on buildings' external envelope – already known to be highly significant in energy demand calculations.

Numerical modelling tools for investigating the neighbourhood scale were further honed by Ratti and Richens (1999) with the addition of new functions that could calculate built form statistics from the DEM; including surface coverage, average built height, sky view factors and shadows. At the same time, by incorporating tools to calculate and display the solar volume for any given plot, Capeluto and Shaviv (2001) were able to demonstrate that even at relatively high built densities - Floor Area Ratios (FARs) of around 1.6 to 1.8 - it was possible to maintain solar access rights to all buildings in a neighbourhood.

From 2000 onwards, improvements allowing models to take account of shading and inter-reflection between buildings, anisotropic sky lighting and greater surface detail were implemented (Mardaljevic and Rylatt, 2003; Robinson, 2006). Most importantly however, models were optimised to become radically more scalable given the finite availability of computing resources (Mardaljevic and Rylatt, 2003; Robinson and Stone, 2004). Montavon et al (2004) demonstrated the usefulness of such inherent scalability by conducting some of the first analyses at the neighbourhood scale, comparing building layouts with respect to daylight effects across three Swiss cities.

A more recent development was the introduction of the concept of 'isosolar surfaces' by Ratti and Morello (2005). Morello and Ratti (2009) later made isosolar surface calculations more extensible and demonstrated their usefulness as a planning tool through calculating the maximum buildable volume of the Milan Trade Fair development site for a given allowable solar obstruction angle. An overview of the methods for calculating the solar envelope and its potential uses for policy guidance is given by Sarkar (2009).

Ratti, Baker and Steemers (2005a) sought to bridge the divide between the older analogue methods of calculating building energy demand, and new computer modelling tools. By integrating algorithms (Richens, 1997) that performed the LT method (Baker and Steemers, 2000) and incorporating parameters to approximate factors such as occupant behaviour, systems efficiency and insulation standards (U-values), Ratti et al (2005b) (2005a) were able to automate the calculation of building energy demand at the hitherto impracticable neighbourhood scale. Initial trials on morphology samples taken from London, Toulouse and Berlin showed that the surface to volume ratio, contrary to some expectations, did not fully describe energy consumption.

The ratio of passive to non-passive zones was shown to be a better indicator, with non-passive zones consuming approximately twice as much energy as unobstructed passive zones – a finding mostly relevant for non-domestic buildings given that non-passive zones in residential buildings tend to be limited or non-existent. Though this had the effect of weakening the relationship between energy consumption and urban morphology, variances as large as 10 per cent were still observed as a result of morphology differences between Toulouse and Berlin. This is still a significant potential energy saving and justified future work towards optimizing urban morphology for reduced energy demand.

2.3 Other contemporary studies

Several other studies have recently focused on using passive solar radiation for lighting and heating. Like this study, they were conducted in a context where most research has produced evidence that increased solar gain is associated with reduced built densities while at the same time leading to greater heat losses. For passive solar house standards, Steemers (2003) highlights a 22 per cent increase in heating energy for a 30 degree obstruction of a south-facing façade compared to an unobstructed façade. At the same time he refers to Yannas (1994) who find 40 per cent higher heat savings when comparing apartments with detached housing and concludes that building densities of a theoretical FAR of 2.5 might represent the optimum density for reducing heat energy demand.

Cheng et al (2006) studied the impact of randomness in the plot layout and height of buildings at high urban densities. By independently varying the randomness of the positional and height parameters in their model, they concluded that randomness in both the vertical and horizontal dimension is beneficial for increasing overall solar access to buildings and surrounding space, with a factor of 3 difference being observed in some cases. This is contrary to the belief by some that increasing urban density will always lead to a deterioration of the immediate environment with respect to solar access.

Kämpf et al (2010) performed multi-objective evolutionary optimisation of building form parameters for terrace flat roof, slab sloped roof and terrace court formations. For each of these, parameters optimised were the height of building facades and the height and orientation of their roofs. Built volume and solar gains were set as the objective functions giving rise to a Pareto front showing the trade-off between built volume and potential solar gains. Basel, Switzerland was selected as the case study site. Results showed that terrace court formation – a perimeter block arrangement of terrace housing with internal courtyards – was the optimal in all trade-off cases.

Okeil (2010) performed a comparison on three types of urban form, described as linear, block and residential solar block (RSB). The RSB formation was a new and optimised building form alleged to be able to maximise the passive solar heating of building facades without overshadowing neighbouring buildings. The forms were compared in simulations of insolation, airflow and urban heat island effects. In a model simulated at 48 degrees latitude, the RSB was found to perform best in these categories.

2.4 Knowledge gaps

As shown above, at the building scale, a number of studies on heat-energy demand have called into question the common sense understanding that more compact building types like apartment blocks outperform small-scale, individual building units most commonly represented by detached, single-family housing (Newton et al., 2000; Utley and Shorrock, 2008). Upon initial inspection these results may seem surprising given the basic physical relationship between heat-energy demand and the function of surface-to-volume ratio or massing of buildings in reducing heat loss. However, these results can be better understood when the more complex trade-offs between the solar heat gains and the surface heat losses of different urban forms are considered. Indeed, this is now well understood at the level of the individual building. The tools have recently become available to move this research up to the scale of the urban block and neighbourhood.

Apart from isolated studies examining the thermal performance of blocks consisting of some of Martin's (1967) archetypal building forms, there is a general lack of studies of the thermal performance of urban morphology types. Perhaps closest to a general study was the work conducted by APUR (2007) and the CSTB (Salat, 2009) into the thermal performance of the Parisian building stock. Though this study was comprehensive, its methodology was based on the classification of buildings by age and not form, making the findings very specific to Paris and, by weak affiliation, other major French cities. Arboit's (2008) study on the city of Mendoza was a good example of the practical application and value of this research field, although again results were specific to low-density buildings in an arid climate. Apart from the work developing the tools and techniques for this field, studies into morphology and thermal performance have been disparate and specific in nature, often concentrating on one sector of a city (Arboit et al., 2008), a subset of urban form (Okeil, 2010) or the effects of a particular morphological parameter (Cheng et al., 2006).

City planners and policy makers do not differentiate the urban fabric by geometric values, but rather by neighbourhood qualities and building types. There is still a lack of a larger body of literature on the general categorisation of urban morphology types in modern European cities, and by extension, a knowledge gap as to the effect of urban morphology type on building heat energy demand. It is the closing of this 'urban geometry gap' (Mitchell, 2005; Ratti et al., 2005a) to which this study aims to contribute.

3 Methodology

3.1 Empirical basis

As the empirical basis for this investigation, 25 different residential building configurations were identified in each of the four largest European cities; London, Paris, Berlin and Istanbul. Although climatic conditions in these cities differ significantly, all have cold winters typically requiring some consideration of heat-energy provision. More importantly, the selection of cities ensured that a wide range of different building types was covered as the four cities represent diverse national building cultures that over centuries have resulted in clear differences in building typologies.

These typologies have mostly emerged over the last 150 years with little or no regard for heat energy demand. The majority of their urban building stock was designed and constructed at a time when a range of other factors determined the shape of the city; when energy was relatively cheap and global warming was not an urgent agenda. Some building configurations even rely entirely on technical, energy intensive heating systems where passive heating and ventilation aids are largely absent. However, whether the impact of morphology on heat energy demand was considered at the design stage or not, today's diversity of existing building stock in European cities allows for a far-reaching comparative analysis.

Following the selection of case study cities, an initial scanning of residential building types and urban morphologies was conducted. The first phase of this process utilised a qualitative approach largely relying on conversations with experts knowledgeable of local architectural styles, building compositions and urban neighbourhoods.

The second phase made use of existing literature and the increasing availability of visual documentations of urban territories including Google Earth and Streetview as well as Microsoft Bing Bird View. Exploring each city via the satellite imagery then allowed the selection of the typologies which were most distinct from a morphological point of view. Both scanning phases informed the choice of the 5 most dominant building typologies featured in each city.

For each dominant building typology, five urban morphology samples were identified in each of the four case study cities – leading to the selection of 100 'real' morphology samples in total.[1] This selection made use of the cataloguing of samples in the previous phase and selected the most homogenous and representative samples for each building type within each city. Priority was given to selecting diverse morphological arrangements within the same broad building typology. All samples were recorded at a scale of 500 by 500 metres, framed to isolate a single and homogenous urban fabric ideally consisting of a single building type (though this was not always possible). Digital Elevation Models (DEM) were used to represent these samples as they allow for both the analysis of the key urban morphology indicators listed below and for the direct facilitation of the energy simulation discussed in the next section (Ratti et al., 2005a).

In addition to using 'real' urban morphology samples as they exist in the four cities, 'idealised' samples were constructed and added to the empirical base. This was critical for 'purifying' the real samples which at a scale of 500 by 500 metres rarely exist in isolation

[1] It is worth a cautionary note that the selection of urban morphology types was a subjective process. Types were categorised according to how people would generally classify buildings and not on any statistical grouping or cluster analysis of built form parameters. Inevitably, there are some ambiguous cases and categorisation is not an exact science.

without interference from other building types and stratified modifications of the original shape of the buildings. In other words, the idealised samples are the distilled and refined morphologies.

The process of creating the idealised samples began by identifying the most basic features of the housing type and reproducing them in the simplest possible way. The basic features being:

- building type (size, volume and shape of the single unit);
- number of floors;
- plot shape and proportion;
- alignments;
- street layout/pattern;
- street width;
- street/ façade proportion;
- aggregation principles of parts;
- size, volume, shape and proportions of blocks (the aggregation of the single units);
- building density (floor area ratio/floor space index);
- coverage ratio (ratio of the sum of the building footprint areas to sample area).

An emphasis on accuracy in the volumetric spatial configuration was included as it is the most important factor in the energy consumption simulation. The methodology to build the idealized samples was based on averages of the main parameters taken from the selected real samples. A single detached housing unit, for example, has been calculated using the average area of every building from each of the five samples for that type. Likewise the number of units composing the ideal sample has been calculated as the average number from the five selected real examples. The height of the buildings has been set using a similar calculation.

While applying these analytical approaches to control the accuracy of each formal factor in the modelling of the idealized sample, the visualization of the ‘image’ of the type, its form and shape were also important. The idealized samples had to ‘look like’ the real samples. Still, the idealisation of samples leads to a loss of information on the typologies and de-contextualizes them from their environment but has the advantage of isolating the impact of their shapes and volumes. In particular, having to decide on a specific orientation of these samples can have significant consequences for energy demands. For each of the five morphology types in each of the four cities, one idealised sample was created from the five real samples of the city’s fabric to give a total of 20 ideal morphology samples.

The quantitative description of all urban morphology samples focuses on five key built environment indicators which were identified for the entire sample area of 500 by 500 metres:

- *building density*, here referred to is Floor Area Ratio (FAR) / Floor Space Index, is defined as the ratio of the sum of the areas of all building floors to that of the sample area (500 by 500 m in this study).
- *building height,* is defined as the average height of buildings within the sample area measured in ‘number of storeys’.
- *building coverage ratio,* though often referred to as just coverage, is defined as the ratio of the sum of the building footprint areas to that of the sample area.
- *surface-to-volume ratio* is defined as the ratio of the envelope of a building (external facades and roof) to the entire volume of that building [sqm/cbm].
- *open space ratio* is defined as the ratio between the un-built area and the gross floor area of any given site.

Other important descriptors of urban form including, for example, the depth of buildings in plan are not included due to resource limitations for this study.

3.2 Heat energy modelling

The energy demand model used for this study follows the principles of an engineering-based, bottom-up model (Swan and Ugursal, 2009). The modelling of theoretical heat energy demands for each of the morphology samples was conducted in two stages. For the first stage, all parameters apart from those pertaining to form were fixed, including the climatic conditions. The simulation then modelled solar heat gains and building surface heat losses. From this, the average annual heat energy demand per square metre of indoor floor space was calculated for each sample. In the second stage, the effects of wall insulation, window U-value and glazing ratio, and climate were analysed.

In order to allow for direct comparisons of all different samples of urban morphology and their theoretical heat energy demand, a scenario was created and applied to all simulations. The climatic conditions were set to that of Paris and building construction values were kept constant throughout (Table 1) leaving only urban morphology itself as the changing variable. Therefore, the effect of the physical dimensions of buildings and their arrangement and layout at a larger scale on theoretical heat energy demand becomes measurable.

Roof	Roof geometry	not considered
	U-value	same as facade value below
Room	Inner temperature	19°C
	Habitable surface	80%
	Ventilation	0.5 h^{-1}
	Night heating coefficient	0.95
	Thermal capacity air	0.34 W/m^3K
	Internal gains	23 kWh/m^2 a.
	Average store height	3 m
External wall	U-value	1.15 W/m^2K
Environment	Vertical solar radiation	410 kWh/m^2
	Heating degree hours	67425 K
Window	Glazing ratio of façade	40%
	U-value	2.8 W/m^2K
	Frame	15% of window area
	Shadowing devices	no
Thermal bridges		Area x 0.05 W/m^2K
Cellar	Excluded	
	Losses reduction factor	0.6

Table 1: Model Assumptions

The heat energy assessment calculation was modelled through GIS software, enabling to combine geometrical aspects and physical simulation within the same model. All our heat energy demand results depend entirely on the predictions of this simulation model. So far, the model used has been tested empirically for individual buildings only but not at the urban scale where actual data availability continues to be limited. Urban morphological factors effecting heat energy demand, including exposure to sun radiation, the spatial and physical dimensions of buildings and their environmental context, were incorporated. This enabled the calculation of the heat energy demand of multiple buildings so that it could be analysed at the chosen scale. Given that average monthly temperatures in all four selected cities were below 26ºC, this energy assessment focused only on heat energy demand rather than energy for cooling. While this is clearly a simplification as temperatures do exceed 26 ºC on individual days, the project objective in this case was to specifically understand the effect of morphology and heat energy demand. It should also be noted that water heating was considered a separate issue to space heating and was not included.

The heat energy demand in buildings can be understood as a direct consequence of the surrounding climatic conditions, the passive heat performance of buildings and the resulting deficit of heat energy required to achieve accepted thermal comfort levels indoors. Energy losses occur via the building envelope when outdoor temperature drops below a reference indoor temperature. These losses derive from the envelope itself, its openings, thermal bridges and losses amassed by ventilation. Energy gains are generated by solar-radiation entering through transparent parts of the building, warming the air of the interior. Gains are also a result of building use: the associated heat generated from either the occupiers themselves or by appliances within the building.

The main variable in assessing the primary heat energy demand is the *outdoor air temperature in relation to the chosen constant inner temperature* which, for this enquiry, has been set to a constant of 19ºC. The heating period is measured according to average annual city air temperatures measured either hourly, daily or monthly. These are described here as heating degree hours (HDH) or heating degree days (HDD), depending on the chosen unit. They are a measure of how many degrees Celsius and for how long (tHp) the outside air temperature (Tex) is lower than the set reference inner temperature (Tin):

$$HDD = \Sigma\ (Tin-Tex) \cdot tHp$$

The primary heat energy demand (HD) is therefore calculated as the difference between heat losses (Htot) and heat gains (Gtot):

$$HD = Htot - Gtot$$

The heat losses are defined as the sum of the losses during the heating period through the building envelope (HT) and the ventilation (HV).

$$Htot = \Sigma\ (Tin-Tex) \cdot tHp \cdot (HT + HV)$$

The heat gains are defined as the sum of the gains during the heating period from the incoming solar radiation (GSun) and the internal gains from dwellers and appliances use (GInt) lowered by their real usage factor (ηp).

$$Gtot = \Sigma\ \eta p \cdot (GSun+GInt) \cdot tHp$$

Heat transmission losses (HT) are expressed as the sum of the losses through the façade (walls and openings), and the heat losses of thermal bridges (HTb). The façade losses are expressed as the thermal conductivity of the building materials (Ui) multiplied by the surface area exposed to the environment (Ai). The thermal conductivity of the building material (Ui) has not been assessed in this work but set as a constant listed with all the other parameter values in the previous section.

$$HT = \Sigma(Ui \cdot Ai) + HTb$$

The thermal bridge losses are expressed as the length of the edges of the building's main form (Li) multiplied by their thermal conductivity coefficient (ψi):

$$HTb = \Sigma\ Li \cdot \psi i$$

This way of assessing losses related to thermal bridges usually leads to an overestimation in buildings with higher insulation standards. A simple correction factor accounted for this. Assuming a certain construction standard, the heat losses through the thermal bridges can be assessed as the average (Ui) value of the façade construction increased by 0.05 W/m^2k . Therefore, the formula becomes:

$$HT = \Sigma\ (Ui \cdot Ai) + 0{,}05 \cdot Ai$$

Using the ESRI-ArcInfo software for the analysis of building information external and adjacent walls can be differentiated. This allows walls that have no contact with the exterior and therefore do not impact on heat energy demand to be removed from the assessment.

Ventilation losses are identified as the volume of air (Vi) exchanged in units overtime (nv), considering its density at a standard temperature and pressure within a room, and defining its thermal capacity as 0.34 Wh/m^3 k. Ventilation can vary widely, but the value of 0.5 cycles per hour has been applied here as a reasonable average.

$$HV = \rho A \cdot cA \cdot nv \cdot Vi$$

It is not necessary or indeed standard practice to heat a building in its entirety, therefore the 'volume' does not refer to the net volume but rather the volume excluding the volume of inner walls, staircases or other uninhabited rooms. The correction value for both the volume and the related floor space has been set to 0.8 of the total, but this is a value that is adjusted to the size and use typology of the building.

To derive the *internal gains*, the value (qi,a) is set according to the German and French standard of 22 kWh/m^2 of inhabitable floor-space area (Ai).

$GInt = qi,a \cdot Ai$

The total *gain from solar radiation* is defined as the incident solar radiation (ISp,i) during the heating period on the different facades of a building. The incident solar radiation has to be defined for each façade separately, and depends on a number of factors:

- orientation of a façade and the relative incident radiation energy (ISp,i);
- the area of transparent elements of a façade (Ai), lowered by the properties of the glazing and resulting transmittance of radiation energy (gi);
- the fraction of area occupied by the frame (FWf,i);
- possible horizontal shading installations (FSh,i) and the shading of outstanding objects (FSs,i).

$GSun = \Sigma\, ISp,i \cdot \Sigma\, FWf,i \cdot FSs,i \cdot FSh,i \cdot gi \cdot Ai$

In the first instance, solar radiation impacting on a vertical surface must be considered. The solar radiation which actually enters a room is quantified according to the proportion of the window frame related to the total window area (FWf,i= 0.85). The physical properties of glass do not allow the transmission of all incident radiation, firstly because the angle of incidence of the radiation is seldom perpendicular, and secondly because glass is never fully transparent due to aging or dust (gi = 0.5). Shadowing generated by other volumes in the vicinity of the building must also be considered as being a major source of influence in accessibility to solar energy within the urban tissue (FSh,i). These values amount to a rigorous assessment of the solar radiation for each façade within their typological context and scale. Horizontal shadowing devices should also be considered if any, though for simplicity we have assumed them as not installed (FSs = 1.0).

Finally, a comprehensive analysis of incoming *solar radiation* for each sample was conducted. The cadastral data, enriched with the height data of the typologies, was transformed into 50cm x 50cm grids. With the urban typologies represented as digital elevation models (DEMs), the incident solar radiation was able to be quantified at each grid point. Calculating solar radiation this way considered all obstructions to direct sun light that are part of the chosen urban morphologies at the neighbourhood scale. During the considered heating period, the penetration rate of solar radiation in the urban tissue is based on the analysis of the sun trajectory during 0.5 hour intervals of the day, aggregated to 14 day averages. Diffuse solar radiation, direct solar radiation and their durations were considered. The outputs of the calculation model are interpolated with the exposed surfaces of each building and normalised to a coefficient ranging between 0 and 1. This is multiplied by the vertical incident solar radiation value of a south facing exposed façade, resulting in a definitive value for the solar radiation of each façade. Among the constant parameters for all sample cities is the vertical incident solar radiation of a south facing exposed façade. All presented results refer to cumulative values for the chosen heating period.

Figure 1: Visualisation of Digital Elevation Model (DEM), solar direct radiation analysis output example and energy demand calculation output example [kWh/sqm/a]

Clearly, this modelling exercise is far from being comprehensive but for the purpose of this study was regarded as appropriate. A critical review of the model can be found in the appendix.

4 Analysis

4.1 Urban Morphology

Overall, similar urban morphologies were identified in all four cities which, at the same time, feature some unique building types. Across the cities, four common morphologies dominate and include those based on detached housing, high-rise apartments, slab housing, and compact urban blocks. City specific morphologies include London’s terraces and Berlin’s row housing, which shared some similarities. The regular urban blocks of Paris feature a lower density version of the city's archetype compact urban block, and the Gecekondu of Istanbul displays a kind of low rise urban housing typology that emerged as a result of the city's organic growth. Furthermore, a separate category was formed for detached multi-unit apartment buildings in Berlin, and for the newer apartments in Istanbul; a dense but modern housing type which is uniquely prevalent across the city and creates a particular morphology.

Figure 2: Figure grounds of key morphology samples

Figure 3: Figure grounds of 'idealised' morphology samples

As introduced above, five quantitative measures of urban morphology were used to describe the samples chosen for this analysis: Building density, building height, surface coverage of buildings, surface-to-volume ratio and open space ratio. A comprehensive visualization of four of these key spatial indicators is facilitated by the so-called Spacemate diagram[2] developed by Berghauser Pont and Haupt (2004) combining floor area ratio, surface coverage, building height and the open space ratio (Figure 4).

Figure 4: SpaceMate diagramm of all real and 'idealised' morphology samples

Our analysis showed clearly that among all samples compact urban blocks combine the highest building densities with low surface-to-volume ratios and high surface coverage. For the identified compact urban blocks, the building densities typically ranged between FAR 1.5

[2] The spacemate diagram simultaneously plots floor area ratio, surface coverage, building height and the open space ratio in one diagram. The surface coverage is assigned to the x-axis and the floor area ratio to the y-axis. These define the two additional parameters building height and open space ratio as gradients expanding across the diagram.

and 2.5 with building heights between 4 and 6 storeys. The most significant exception was Paris where this value ranged between FAR 4 and 5.2 and heights between 7 and 9 storeys. The surface coverage of compact urban blocks is relatively high and usually ranges between 30 and 60 per cent. The idealised samples displayed the same overall patterns in all four cities.

Our urban morphology samples also confirmed that detached housing combines the lowest building densities with high surface-to-volume ratios and low surface coverage. Unsurprisingly, detached housing in all four cities featured by far the lowest building densities with typical FARs of below 0.5. Again, the idealised samples displayed the same overall patterns.

Furthermore, the analysis identified high-rise apartments and slab housing as sharing a potential for low surface coverage and a wide range of building densities and surface-to-volume ratios. The overall pattern for high-rise apartments and slab housing within and across the four cities was less clear. This was likely compounded by the fact that these urban morphologies were the least likely to exist in isolation within the 500 by 500 m sample areas. For both, density typically varied between a FAR of 0.6 to 1.7, with a tendency toward higher densities for high-rise compared to slab housing. Surface coverage of both configurations ranged from 10 to 20 per cent, similar to that of detached housing. Idealised samples tended to consist of higher FARs and lower coverage than the real samples, hinting at the lack of purity of the morphologies in the real samples.

Of further interest was terrace housing in London which combines relatively low density with relatively low surface coverage and a range of surface-to-volume ratios while row housing in Berlin has slightly lower surface coverage at same density levels with little surface-to-volume variation.

Finally, Gecekondu in Istanbul and regular urban blocks in Paris feature wide spread densities and surface coverage values. Gecekondu density spanned from FAR 0.4 to 1.8 with coverage from 25 to just above 40 per cent. Regular urban blocks in Paris were significantly denser, ranging from FAR 1.8 to 3.4 and coverage between 15 and 35 per cent. The idealised samples displayed the averages of these values in both cases.

To conclude, density is achieved either through increasing the average building height or overall surface coverage, but rarely simultaneously. While density can be seen to increase steadily up to approximately FAR 1, between FAR 1 and 1.5 there appears to be a bifurcation of the data points. Past this point, the morphology types appear to either follow a path of fast height increase with increasing density, or one of very little height increase with increasing density. It is the high rise apartment and slab housing formations which tend to follow the former path, with the regular urban blocks of Paris, the modern apartments of Istanbul and the compact urban blocks of all cities following the latter. This alludes to a mutual exclusivity in design choices (as regulated for by the planning laws in all four cities) – if one wishes to increase density, one can either build upwards or increases the surface coverage of the building. The data suggests that these two strategies are seldom attempted in unison.

4.2 Heat Energy Demand Modelling

Overall, the hypothesis that different building morphologies feature distinctively different energy demands and that higher density building configurations lead to greater heat-energy efficiency was confirmed. The ratio between the least and best performing sample is greater than factor six, emphasising the significance of a better understanding of design-related impacts on heat-energy demands. The average building height and building density were found to be good indicators for heat energy efficiency, each correlating negatively with the heat energy demand. The surface-to-volume ratio also correlates well but positively with heat energy demand. The correlation coefficients presented below are first aggregated over all samples and then shown as a breakdown by city and by morphology type. Morphology types which were unique to only one city were omitted as, with so few data points, related results would not be statistically significant. The Pearson correlation formula was used to calculate these values.

Figure 5: Correlation with heat energy demand by typology and by city

The absolute results for the theoretical heat energy demand presented below are measured in kWh per square metre per year.[3] The distribution of heat demand in all 100 samples in the four cities followed a standard normal distribution with an average of 103 kWh/sqm/a. The highest heat energy demand was calculated for a Gecekondu housing area in Istanbul with 194 kWh/sqm/a, while the lowest value, at about 30 kWh/sqm/a, was identified for an area of compact urban blocks in Paris. The distribution of the 20 idealised samples tended towards lower energy efficiency than the real samples with an average heat energy demand of 119 kWh/sqm/a and a range of between 60 and 238 kWh/sqm/a. These results might also be informed by an effect whereby a greater mix of different urban typologies has been identified as an overall advantage for energy efficiency (Cheng et al., 2006).

Looking at *building typologies*, compact urban blocks consistently perform best, detached housing worst. The majority of compact urban blocks displayed a heat energy demand of less than 100 kWh/sqm/a and in the case of Paris even below 50 kWh/sqm/a. High-rise apartments and slab housing can potentially perform very well. With the exception of London slab housing and Berlin high rise apartments, all idealised samples of these morphology types showed heat energy demands of less than 80 kWh/sqm/a. The real samples of high rise apartments seemed to underperform due to the fact that they rarely exist in a pure form within

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[3] These are theoretical energy values only comparable across the results of the modelling undertaking as part of this study. They cannot be compared to the real energy performances of buildings.

the 500 by 500 metres sample areas. The same phenomenon was observed for slab housing, particularly for the case of London and Paris, where real samples tended to generate heat energy demands as high as 150 kWh/sqm/a, while idealising the samples pushed this value down to 105 and 80 kWh/sqm/a respectively. Urban morphologies that featured the most diverse energy performances included the Gecekondu areas in Istanbul, with heat energy demands ranging between 100 and 200 kWh/sqm/a, apartment buildings in Berlin ranging between 90 to 170 kWh/sqm/a, and slab housing in Paris and London ranging between 60 to 150 kWh/sqm/a and 85 to 150 kWh/sqm/a respectively.

Figure 6: Building typology and heat energy demand

With regards to *density*, the impact of increasing densities is greatest at the lowest density levels. Those morphologies with the lowest densities (under FAR of 0.5) display a heat-energy demand of at least 100 kWh/sqm/a easily reaching almost 200 kWh/sqm/a.. At the same time, efficiency levels of less than 50 kWh/sqm/a are common only above FAR 4 although idealised samples in Paris and Berlin seem to suggest similar efficiency achievements at densities as low as FAR 1. Minimum building density appears to guarantee the maximum heat-energy demand. For all samples with a density of above FAR 1.5, heat energy demand was significantly below 100 kWh/sqm/a (with only two exceptions, both in Istanbul). All morphologies at density levels above FAR 4 have performances that vary between 30 and 50 kWh/sqm/a only. Greatest variation in energy demand was found at a density of FAR 1 where it ranged from 50 to 150 kWh/sqm/a.

Figure 7: Building density and heat energy demand

Increasing *surface-to-volume ratio* increases the range of energy demand in buildings. These variations in heat energy demand at similar surface-to-volume ratios hint at the trade-off between surface heat losses and solar gains which both scale positively with building surface area. At a ratio of 0.15 the range in energy performance is only 35 to 80 kWh/sqm/a, while at a ratio of 0.4 this increases to a range of near 110 to 200 kWh/sqm/a.

Average building height was found to be a proxy indicator of heat energy demand. This variable was found to best fit a logarithmic relationship with heat energy demand decreasing with increasing height. Paris demonstrates the greatest average height with more than half of the morphologies sampled being above 6 floors. Conversely, London demonstrates the lowest average height with more than half lying below 4 floors. A corresponding difference in heat energy demand is seen with Parisian compact urban blocks achieving only 30 kWh/sqm/a, while the equivalent morphology in London achieves 70 kWh/sqm/a at its lowest.

4.3 The impact of insulation, glazing ratio and climate

Insulating walls should result in greater absolute energy saving if the original through-wall energy losses (and thus heat energy demand) are high. As one would expect, modelling results showed that insulating a building which has higher initial heat energy demands results in a greater absolute reduction in that heat energy demand. Berlin detached housing shows a heat energy demand of 393 kWh/sqm/a at the high u-value of 2, reducing to 118 kWh/sqm/a at the low u-value of 0.5; resulting in a net saving of 275 kWh/sqm/a. By comparison, the Parisian compact urban block has a heat energy demand of 97 kWh/sqm/a with a wall u-value of 2, reducing to 37 kWh/sqm/a when the u-value is reduced to 0.5; a net energy saving of 60 kWh/sqm/a. However, the relative difference in heat energy demand between the selected detached and compact housing only reduces from about a factor 4 to 3.2 for the two extreme u-values. Also, there is of course more wall area to insulate per unit volume in detached housing, so this will be more expensive and includes higher embedded energy.

Figure 8: Changing u-values and heat energy demand

The glazing ratio is another important factor for the overall heat energy performance of buildings and indicates the proportion of the building which is covered by windows. As the glazing ratio is increased, heat loss through windows, which is usually much greater than that which is lost through walls, increases. But solar heat gains through the windows also increase. The balance of the two is dependent on the window u-value; the rate at which heat is lost through the windows. Given the relationship described above there can exist a window u-value above which any further increase in glazing ratio would result in a net energy loss through the windows and thus an increase in heat energy demand. Conversely, below this u-value, any further increase in glazing ratio would result in net solar gains and thus a reduction in heat energy demand. The point at which this critical u-value is reached is dependent on the form of the building and the surrounding morphology. Our analysis showed that more linear building forms such as row housing, slab housing and terraced housing show the highest critical window u-values while compact urban blocks and detached housing tend to have similar critical window u-values. This seems to imply that the compactness of the building form is not in itself an important factor in critical u-value determination. It seems more likely that a morphology's solar cross-section relative to its volume is a more important indicator of the critical window u-value.

Figure 9: Critical window u-values of different urban morphology types

In the absence of the effects that changing latitude may have, the effect of climate is mainly a scaling one with overall factor differences between the heat energy demand of different urban morphologies being only marginally affected. The colder the climate the greater the heat energy demand of the buildings. For example, compact urban blocks in Paris displayed a range of 90 to 38 kWh/sqm/a compared to detached housing in Berlin with 321 and 165 kWh/sqm/a. When comparing the relative difference in heat energy demand for the two extreme cases, Berlin's and Istanbul's climatic conditions, the values for the selected detached and compact housing increases from about a factor 3.6 to 4.3. With a maximum of 4˚ difference between the latitudes of London (52˚), Paris (49˚) and Berlin (53˚), the effect of latitude is justifiably small. However, with Istanbul at a latitude of 41˚, the effects of the angle of the sun may have a noticeable impact on the overshadowing of buildings – the sun will be higher in the sky and thus shadows will generally be shorter.

Figure 10: Climatic conditions and heat energy demand

5 Conclusions

In summary, the theoretical results of this study suggest that urban morphology induced heat energy efficiencies are significant. Our main analysis with fixed parameters for all variables except urban form resulted in theoretical heat energy demand variances for extreme cases of up to a factor 6. Differences of factor 3 to 4 were common across the most typical urban morphologies in each city and persisted for different insulation standards and climatic conditions. This seems to be in line with an assumption by Ratti et al (2005a) that design related characteristics might explain variations of up to factor 5 (factor 2.5 for building design and factor 2 for urban geometry). Our findings do, however, diverge from their analysis for Berlin, Toulouse and London which also included lighting where urban geometry only explained a variance of 10 per cent.

Overall, our research identifies significant heat energy efficiencies that are achieved by either higher building densities (for example compact urban blocks) or by taller buildings that in turn allow for lower building densities (as low as a FAR of 1). In contrast to previous work, this research did not find any effects whereby increasing density decreases heat energy efficiency – a finding that is certainly important to verify in future follow-up research. Here, it is particularly relevant to investigate potential trade-offs with other building energy demands such as for lighting and cooling which might have negative density associations. The study also highlighted that both the variance in heat energy demand and the diversity of urban morphologies is greatest for all four case study cities at a density level of FAR 1. Very tentative evidence which emerged from comparing our results for the real urban morphology samples with the 'purified' samples seems to further confirm previous work that suggested higher heat energy efficiencies for mixes of building typologies. Again, this seems extremely relevant for future work.

From a methodological perspective, our research confirmed the usability of digital elevation models (DEM) for both, an analysis of key urban morphology descriptors as well as GIS enabled simulations of heat energy demand. We also regard this work as an encouraging contribution to the on-going development of bottom-up models (Swan and Ugursal, 2009) that help to determine energy end-use in cities.

Word count: 7,998

Appendix

A - Figures

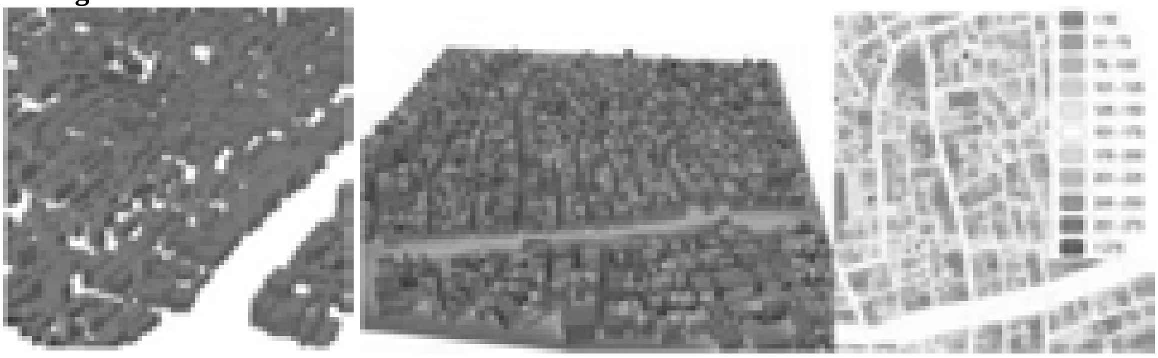

Figure 1: Visualisation of Digital Elevation Model (DEM), solar direct radiation analysis output example and energy demand calculation output example [kWh/sqm/a]

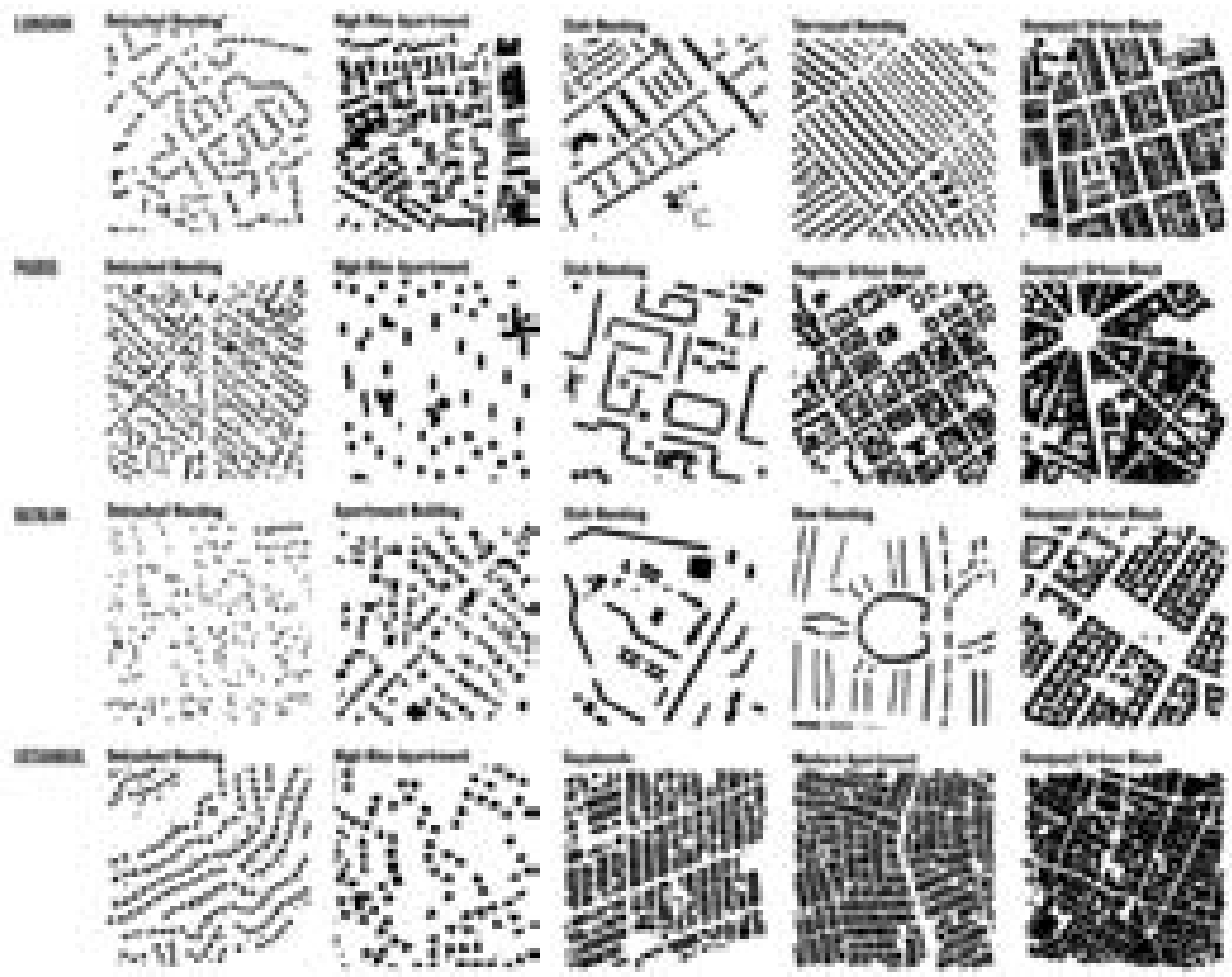

Figure 2: Figure grounds of key morphology samples

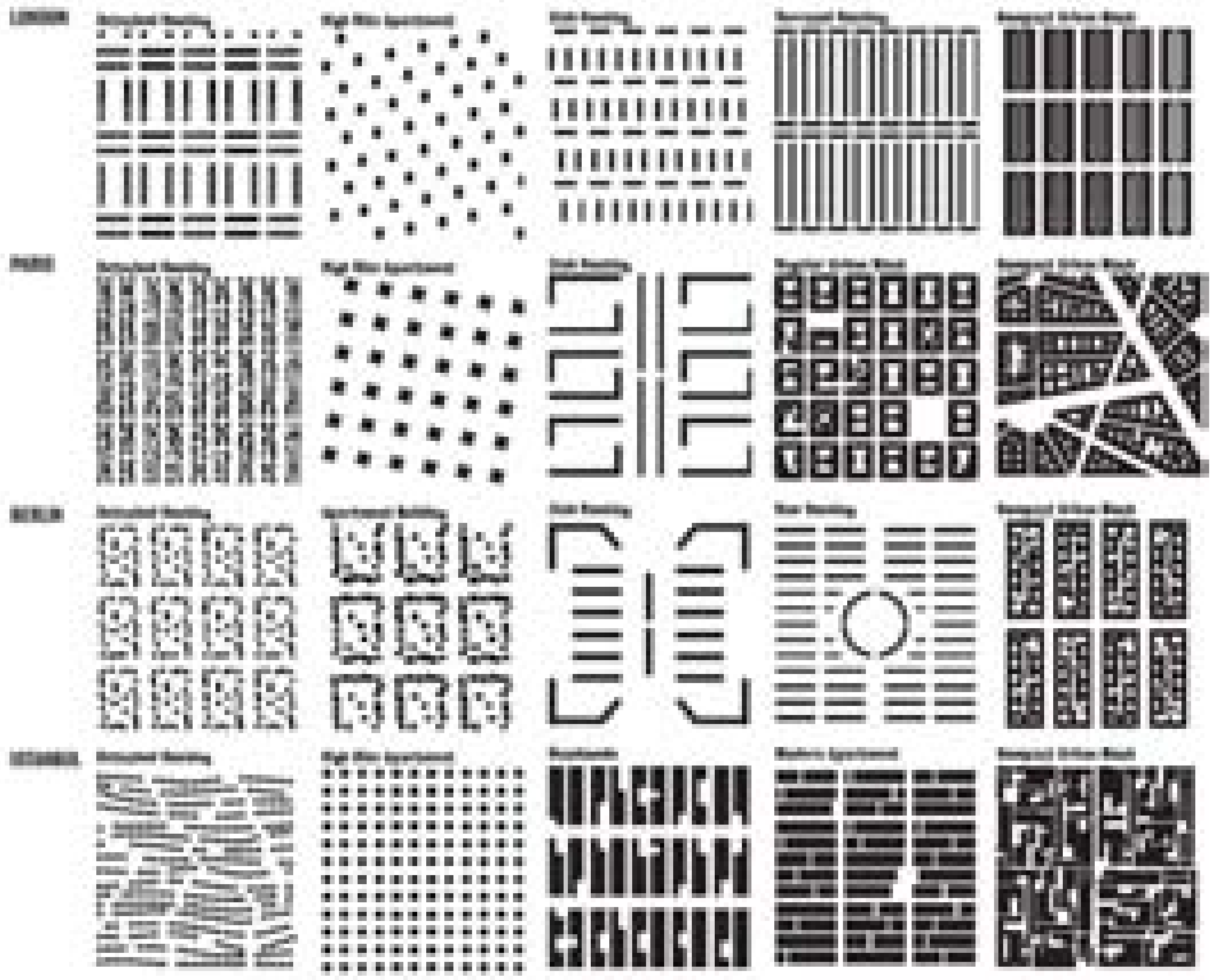

Figure 3: Figure grounds of ‘idealised’ morphology samples

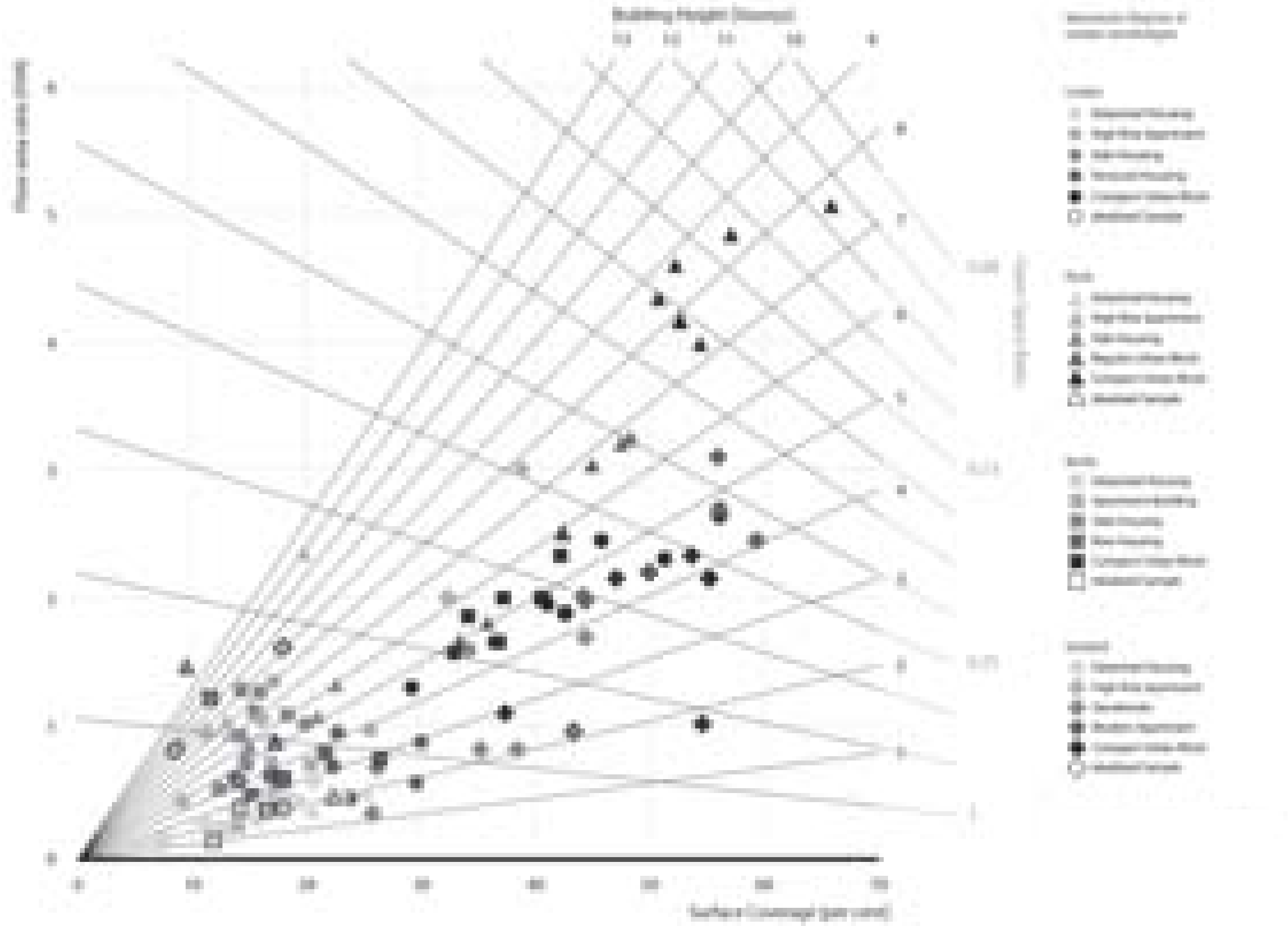

Figure 4: SpaceMate diagramm of all real and 'idealised' morphology samples

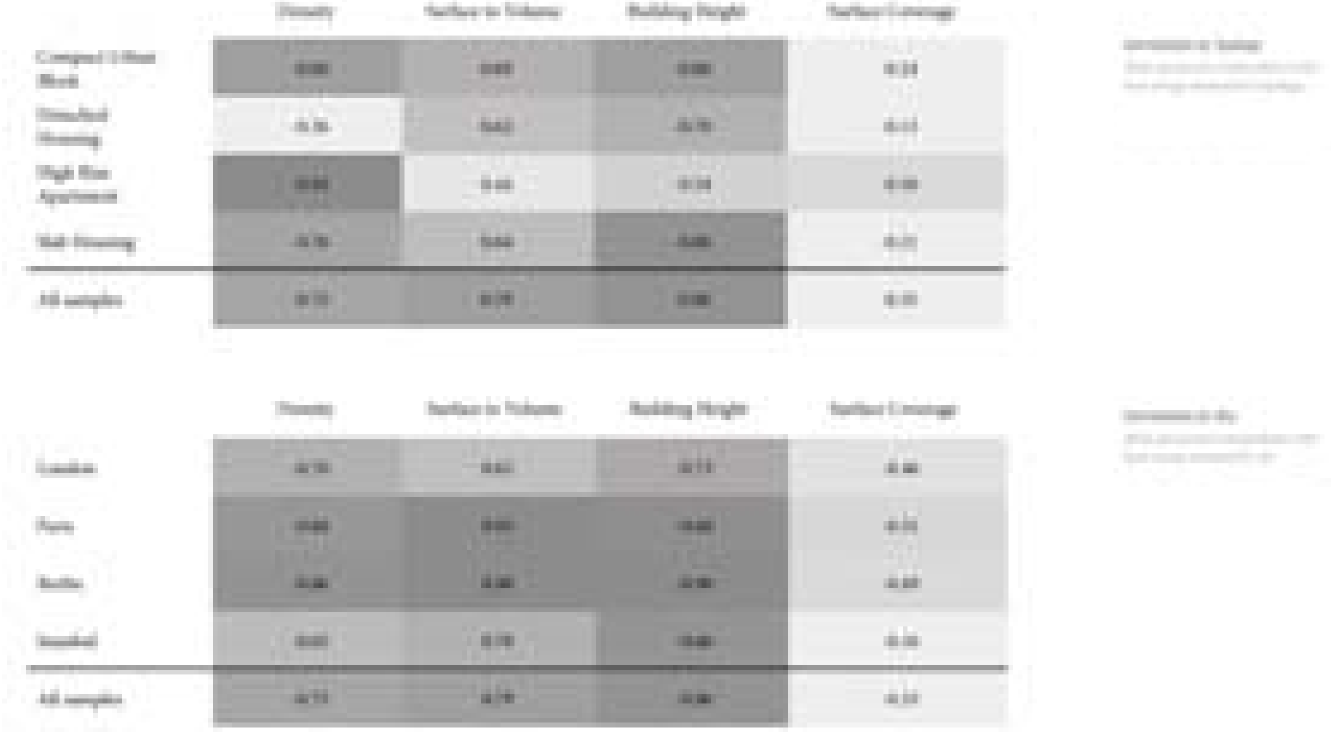

Figure 5: Correlation with heat energy demand by typology and by city

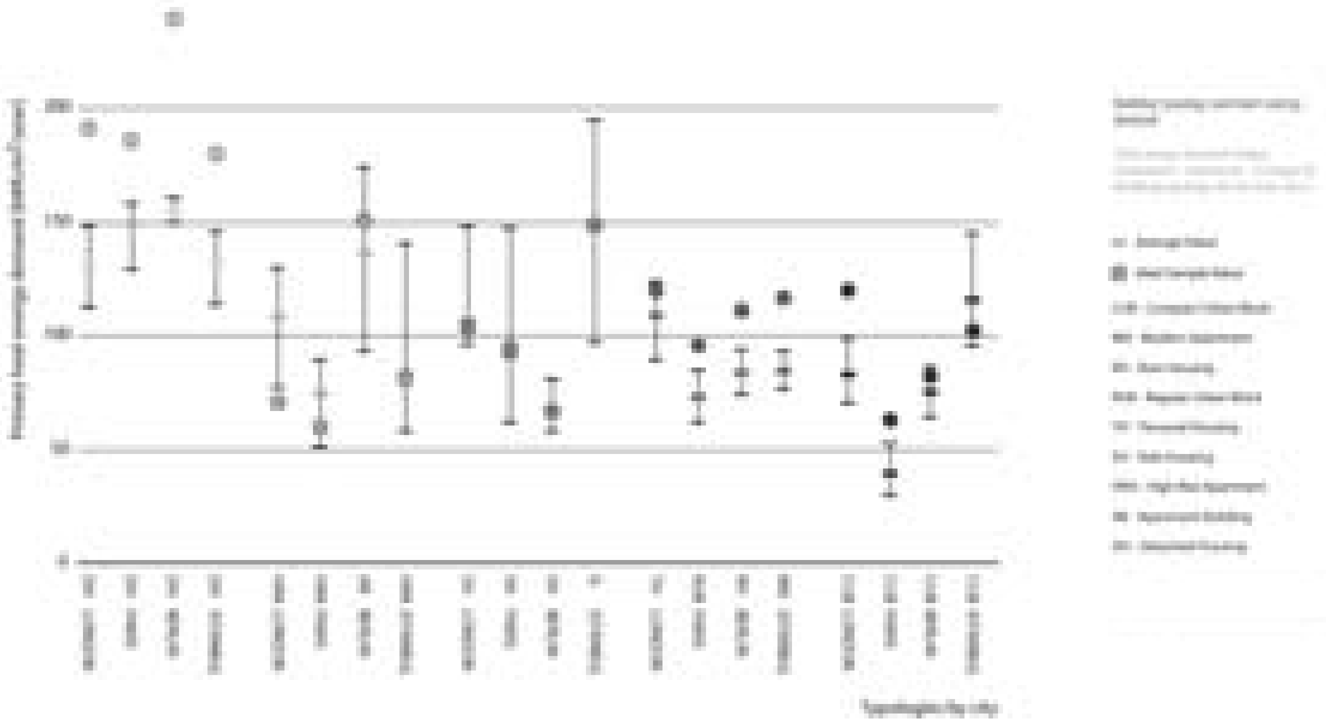

Figure 6: Building typology and heat energy demand

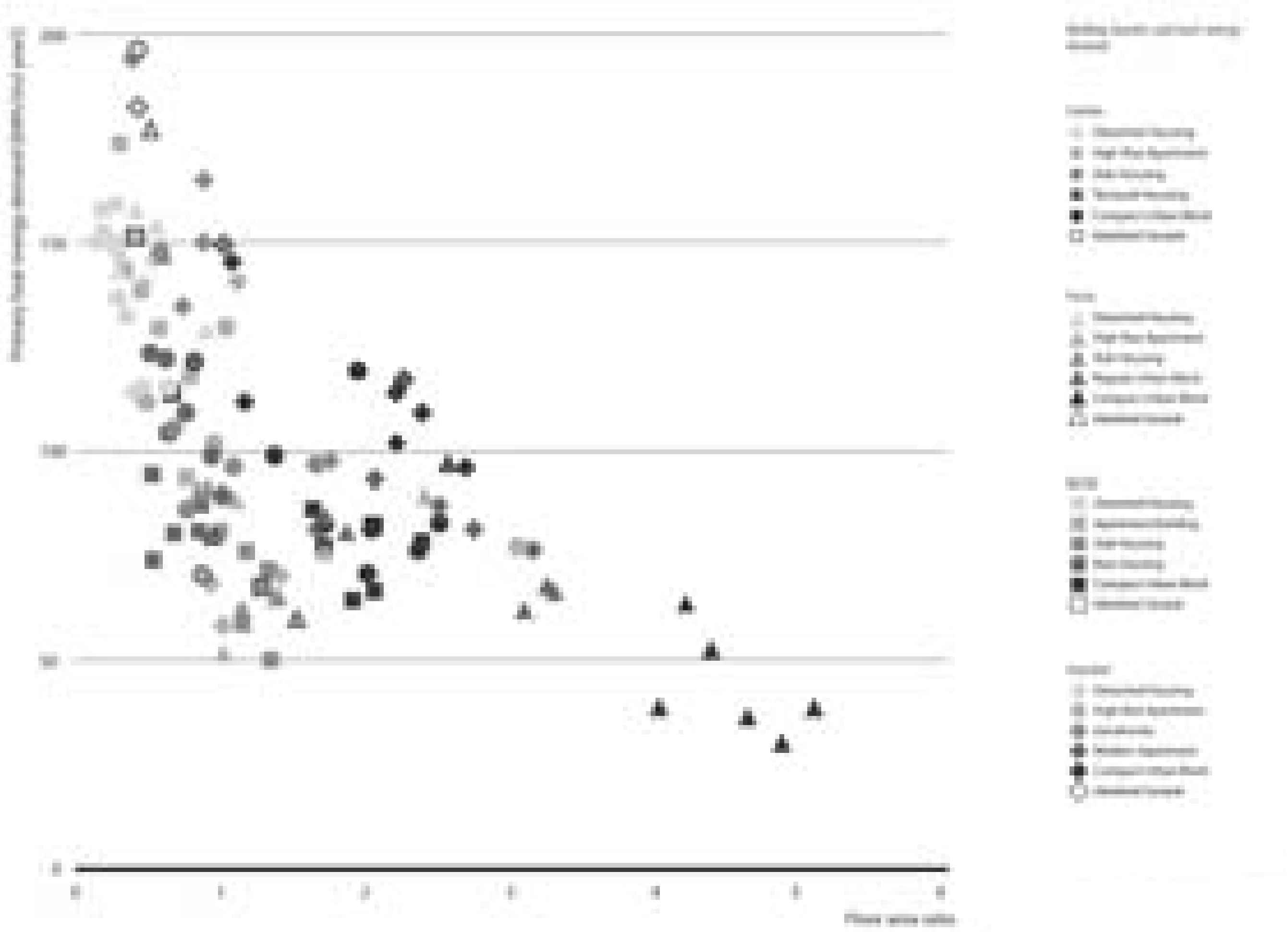

Figure 7: Building density and heat energy demand

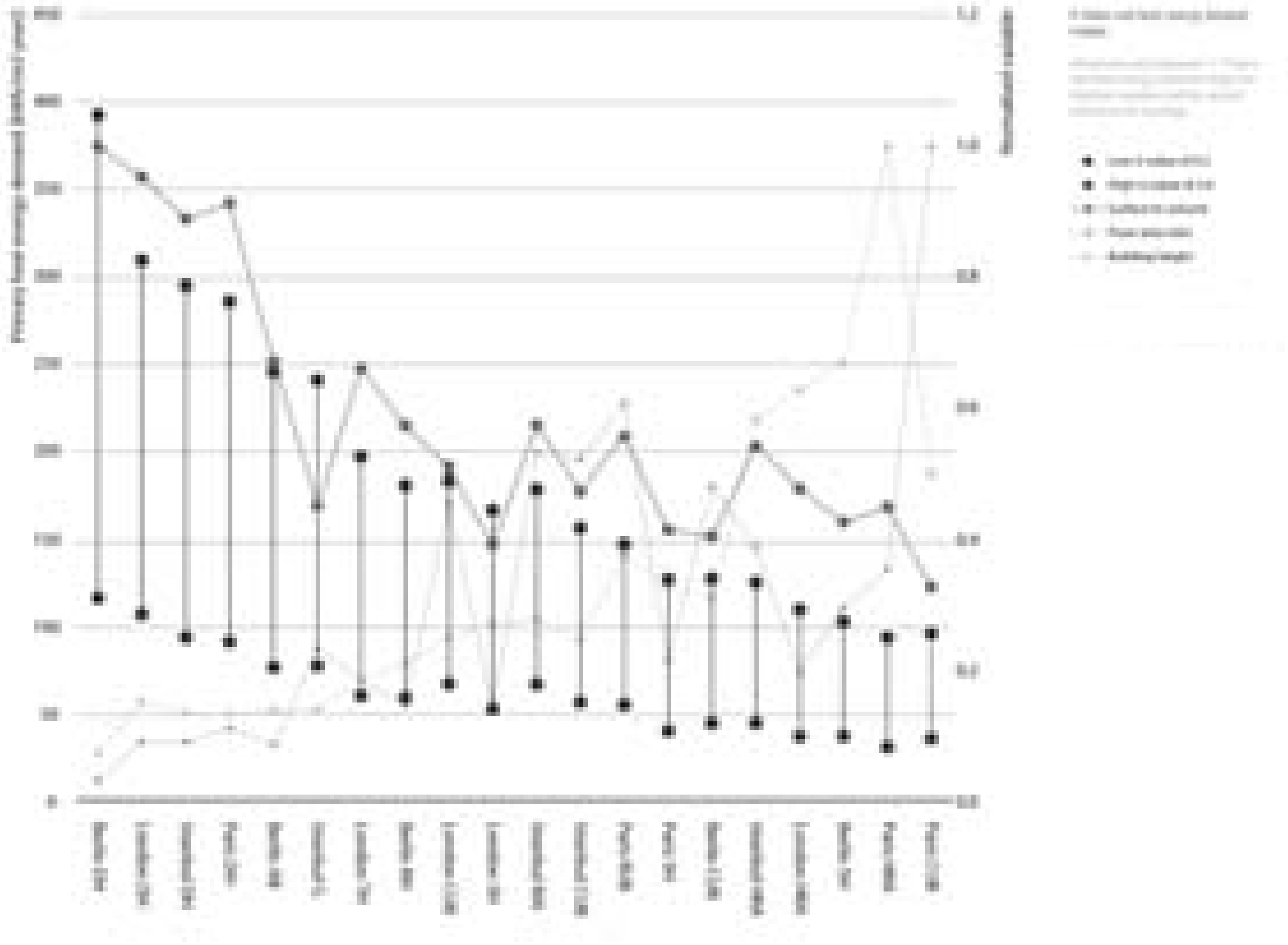

Figure 8: Changing u-values and heat energy demand

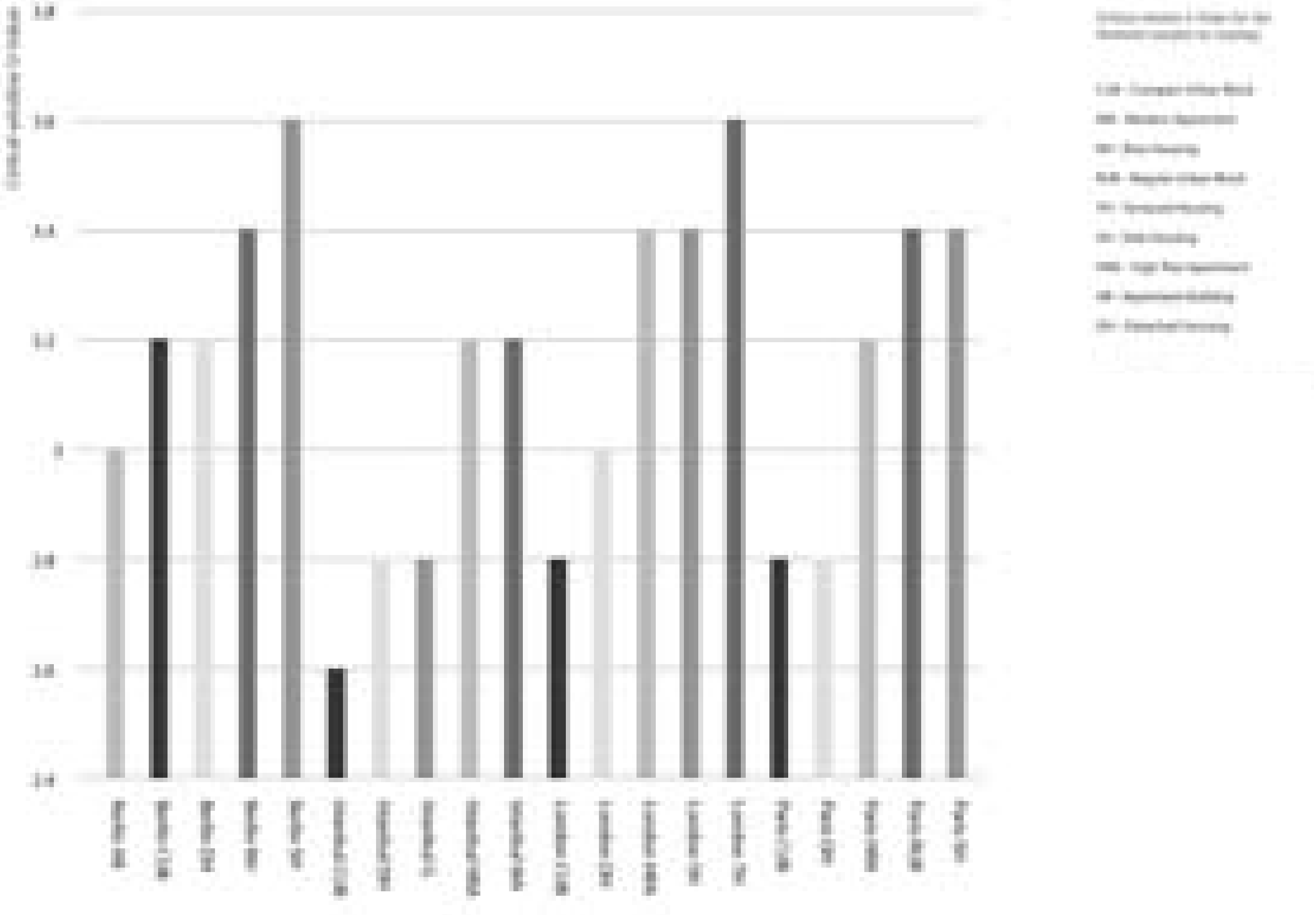

Figure 9: Critical window u-values of different urban morphology types

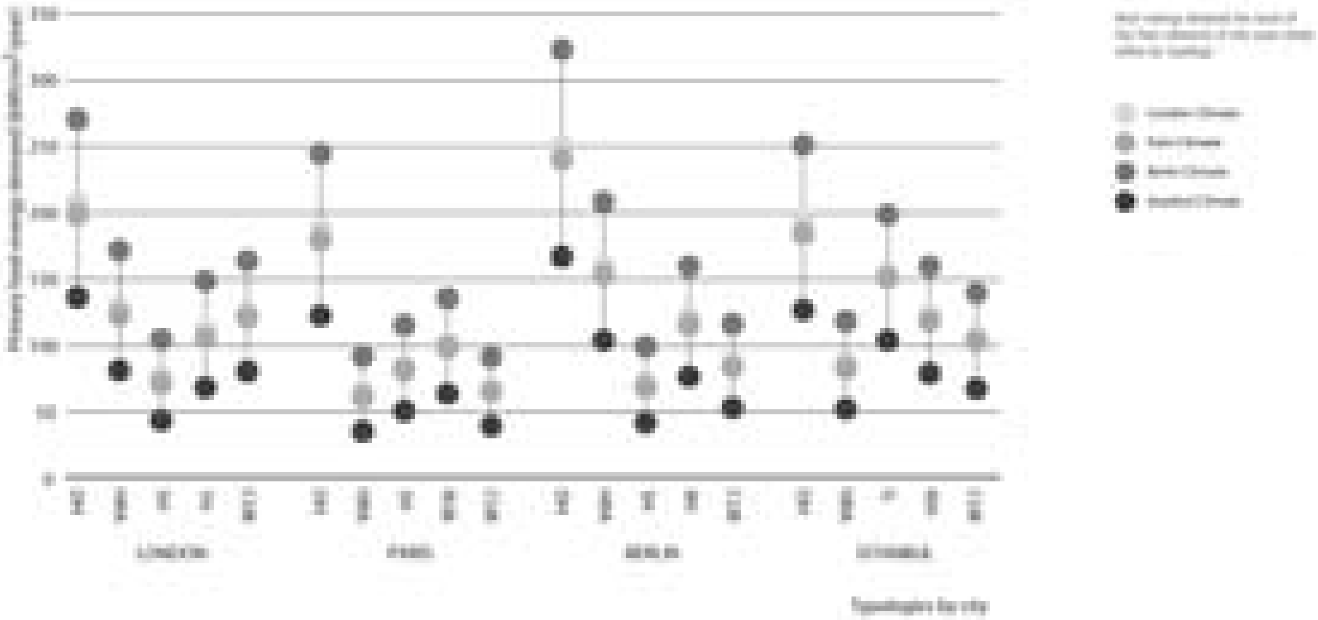

Figure 10: Climatic conditions and heat energy demand

B – Summary table of key results

CITY	TYPOLOGY	NEIGHBOURHOOD	COVERAGE RATIO	FLOOR-AREA RATIO	SURFACE / VOLUME RATIO	AVERAGE BUILT HEIGHT (Floors)	HEAT ENERGY DEMAND (kWh/sqm/a) (Paris)	HEAT ENERGY DEMAND (kWh/sqm/a) (Istanbul)	HEAT ENERGY DEMAND (kWh/sqm/a) (London)	HEAT ENERGY DEMAND (kWh/sqm/a) (Berlin)
London	Detached Housing	East Finchley	0.14	0.43	0.31	3.04	112.15			
		Bickley	0.11	0.25	0.40	2.09	148.29			
		Falconwood	0.16	0.31	0.38	1.99	132.46			
		Arnos Grove	0.12	0.25	0.37	1.97	136.65			
		Putney	0.20	0.61	0.36	2.99	115.01			
		Idealized Sample	0.14	0.39	0.40	2.50	196.62	134.52	205.69	268.51
	High Rise Apartment	Kennington	0.09	0.45	0.26	3.70	111.46			
		Euston	0.17	0.92	0.25	4.26	101.58			
		Latimer Road	0.17	0.76	0.24	3.57	117.81			
		Barbican	0.39	3.04	0.14	5.76	77.08			
		Camberwell	0.25	1.01	0.58	3.00	129.55			
		Idealized Sample	0.08	0.84	0.20	10.08	70.25	42.20	74.71	103.41
	Slab Housing	Pimlico	0.20	1.06	0.26	4.26	95.97			
		Walworth	0.15	0.73	0.26	4.63	86.04			
		Manor House	0.12	0.55	0.29	2.63	147.77			
		Kidbrooke	0.14	0.64	0.25	4.30	105.18			
		Bayswater	0.34	1.64	0.18	3.89	96.50			
		Idealized Sample	0.14	0.61	0.17	4.40	104.14	67.20	109.63	146.98
	Terraced Housing	Edmonton	0.24	0.48	0.32	2.01	123.34			
		Clapham South	0.30	0.91	0.31	3.00	98.54			
		Tooting	0.29	0.59	0.31	2.00	121.98			
		Kennington	0.22	0.73	0.42	2.94	109.01			
		Notting Hill	0.23	0.98	0.25	4.05	89.34			
		Idealized Sample	0.26	0.79	0.28	3.00	121.29	79.57	127.73	170.40
	Compact Urban Block	Victoria	0.36	1.69	0.22	4.18	82.34			
		Marylebone	0.51	2.35	0.20	4.21	76.23			
		Paddigton	0.46	2.49	0.32	4.31	82.72			
		Backer Street	0.41	1.99	0.15	4.17	70.59			
		West Kensington	0.29	1.35	0.16	3.99	98.60			
		Idealized Sample	0.42	1.93	0.22	4.06	119.02	78.90	123.75	162.16

CITY	TYPOLOGY	NEIGHBOURHOOD	COVERAGE RATIO	FLOOR-AREA RATIO	SURFACE / VOLUME RATIO	AVERAGE BUILT HEIGHT (Floors)	HEAT ENERGY DEMAND (kWh/sqm/a) (Paris)	HEAT ENERGY DEMAND (kWh/sqm/a) (Istanbul)	HEAT ENERGY DEMAND (kWh/sqm/a) (London)	HEAT ENERGY DEMAND (kWh/sqm/a) (Berlin)
Paris	Detached Housing	Satrouville	0.23	0.52	0.36	2.08	154.05			
		L┤Etrang-la-ville	0.14	0.26	0.35	1.89	143.26			
		Taverny	0.20	0.38	0.37	1.84	158.09			
		Le Blanc-Mesnil	0.25	0.52	0.34	1.96	154.39			
		Maison Alfort	0.28	0.87	0.32	2.87	128.90			
		Idealized Sample	0.22	0.48	0.39	2.17	177.46	120.68	185.67	242.95
	High Rise Apartment	La Defense	0.14	1.35	0.20	9.49	64.71			
		Creteil Universite	0.13	1.08	0.18	8.41	88.46			
		Epinay sur Seine	0.18	1.69	0.16	6.73	76.03			
		Val de Fontenay	0.13	0.99	0.19	7.76	51.48			
		Porte de Choisy	0.20	2.39	0.16	10.18	89.51			
		Idealized Sample	0.09	1.50	0.19	16.06	59.72	34.22	64.07	90.62
	Slab Housing	Nanterre Ville	0.15	0.81	0.20	4.50	90.37			
		Gare de Gros Noyer	0.12	0.57	0.23	3.01	147.00			
		Garges Sarcelles	0.21	1.12	0.18	5.61	62.20			
		Creteil Prefecture	0.15	0.88	0.24	5.08	91.06			
		Villepinte	0.22	1.37	0.18	5.95	65.35			
		Idealized Sample	0.17	0.91	0.18	5.31	79.64	49.51	83.82	113.64
	Regular Urban Block	Anatole France	0.45	3.09	0.19	6.54	61.94			
		Saint Denis	0.36	1.85	0.21	5.13	80.75			
		Aubervilles	0.33	1.71	0.21	4.50	84.55			
		Buzenval	0.48	3.30	0.18	6.48	66.38			
		Vincennes	0.47	3.24	0.20	6.66	67.86			
		Idealized Sample	0.42	2.55	0.24	6.06	96.71	62.41	100.98	134.16
	Compact Urban Block	Saint Placide	0.52	4.65	0.15	8.64	36.13			
		Bonne Nouvelle	0.66	5.11	0.14	7.61	38.35			
		Courcelles	0.57	4.88	0.11	8.39	29.83			
		Saint Ambroise	0.54	4.03	0.14	7.34	38.51			
		Victor Hugo	0.51	4.39	0.16	8.20	52.35			
		Idealized Sample	0.52	4.21	0.14	8.04	63.41	38.13	66.19	89.84

CITY	TYPOLOGY	NEIGHBOURHOOD	COVERAGE RATIO	FLOOR-AREA RATIO	SURFACE / VOLUME RATIO	AVERAGE BUILT HEIGHT (Floors)	HEAT ENERGY DEMAND (kWh/sqm/a) (Paris)	HEAT ENERGY DEMAND (kWh/sqm/a) (Istanbul)	HEAT ENERGY DEMAND (kWh/sqm/a) (London)	HEAT ENERGY DEMAND (kWh/sqm/a) (Berlin)
Berlin	Detached Housing	Alt-Karow	0.05	0.11	0.44	2.06	150.17			
		Falkenhorst	0.12	0.23	0.38	1.92	150.22			
		Heiligensee	0.13	0.24	0.41	1.87	159.22			
		Machnow	0.07	0.15	0.42	2.03	157.99			
		Hönower Siedlung	0.07	0.15	0.42	2.00	152.79			
		Idealized Sample	0.12	0.14	0.42	1.22	238.41	165.28	248.43	321.32
	Apartment Building	Neu-Westend	0.17	0.54	0.25	2.65	129.32			
		Grünewald	0.20	0.73	0.23	3.42	93.34			
		Lankwitz	0.14	0.30	0.36	2.08	143.15			
		Hermsdorf	0.17	0.41	0.32	2.33	138.42			
		Rudow	0.14	0.27	0.42	1.87	173.89			
		Idealized Sample	0.16	0.38	0.28	2.29	151.49	102.27	157.92	206.28
	Slab Housing	Marienfelde	0.16	1.30	0.22	9.27	71.64			
		Märkisches Viertel	0.14	1.32	0.18	10.18	49.79			
		Lichtenberg	0.15	1.15	0.17	6.20	75.90			
		Wartenberg	0.18	1.12	0.17	6.53	58.42			
		Marzahn	0.14	0.96	0.16	5.75	80.75			
		Idealized Sample	0.11	1.26	0.18	10.74	67.34	40.44	71.11	97.73
	Row Housing	Gartenstadt Falkenhöh	0.15	0.50	0.20	3.19	73.86			
		Reinickendorf West	0.21	0.84	0.20	3.67	87.29			
		Hufeisensiedlung Britz	0.15	0.49	0.25	2.98	93.97			
		Haselhorst	0.22	0.82	0.23	3.85	80.80			
		Neu-Karow	0.17	0.65	0.21	3.90	80.25			
		Idealized Sample	0.18	0.63	0.24	3.43	113.82	74.65	119.12	157.85
	Compact Urban Block	Charlottenburg	0.34	1.89	0.19	5.49	64.26			
		Moabit	0.33	1.61	0.19	4.61	86.14			
		Friedenau	0.37	1.69	0.16	4.25	77.27			
		Neukölln	0.37	2.04	0.19	5.38	66.46			
		Prenzlauer Berg	0.42	2.37	0.16	5.01	78.37			
		Idealized Sample	0.40	2.03	0.17	5.03	82.14	51.83	85.73	114.67

CITY	TYPOLOGY	NEIGHBOURHOOD	COVERAGE RATIO	FLOOR-AREA RATIO	SURFACE / VOLUME RATIO	AVERAGE BUILT HEIGHT (Floors)	HEAT ENERGY DEMAND (kWh/sqm/a) (Paris)	HEAT ENERGY DEMAND (kWh/sqm/a) (Istanbul)	HEAT ENERGY DEMAND (kWh/sqm/a) (London)	HEAT ENERGY DEMAND (kWh/sqm/a) (Berlin)
Istanbul	Detached Housing	Acarkent	0.14	0.36	0.31	2.51	113.86			
		Küçük Çamlıca	0.16	0.43	0.28	2.75	115.33			
		Levent	0.19	0.43	0.33	2.20	140.07			
		Beylerbeyi	0.11	0.28	0.31	2.34	145.66			
		Yeniköy	0.18	0.50	0.31	2.51	145.69			
		Idealized Sample	0.18	0.39	0.38	2.20	182.64	124.61	190.75	248.80
	High Rise Apartment	Erenköy	0.32	2.03	0.25	6.46	81.06			
		Bahcesehir	0.09	0.90	0.23	10.18	68.12			
		Kagıthane	0.16	1.09	0.22	4.40	140.56			
		Ugur Mumcu	0.17	1.39	0.25	7.69	70.02			
		Basaksehir	0.11	0.99	0.24	9.04	58.07			
		Idealized Sample	0.18	1.65	0.23	9.34	81.32	50.51	85.94	117.07
	Gecekondu	50. Yıl	0.44	1.74	0.25	3.76	97.25			
		Ertugrulgazi	0.26	0.35	0.38	1.29	194.36			
		Altınsehir	0.26	0.71	0.28	2.47	134.66			
		Gülensu	0.38	0.85	0.33	1.99	165.13			
		Sultanbeyli	0.35	0.85	0.29	2.16	150.05			
		Idealized Sample	0.43	0.99	0.19	2.30	149.51	102.15	153.73	196.72
	Modern Apartment	Nenehatun	0.44	2.05	0.22	4.29	93.06			
		Nuripasa	0.56	2.74	0.21	4.68	81.28			
		Oruçreis	0.59	2.49	0.24	4.09	86.99			
		Zafer	0.56	3.15	0.23	5.45	76.29			
		Denizköskler	0.44	2.02	0.24	4.46	81.02			
		Idealized Sample	0.50	2.25	0.24	4.51	116.90	77.67	121.10	157.89
	Compact Urban Block	Tophane	0.47	2.19	0.24	4.09	113.70			
		Tarlabası	0.53	2.37	0.28	4.16	108.90			
		Kasap Demirhun	0.54	1.05	0.24	4.70	145.37			
		Kumkapı	0.56	2.68	0.20	4.02	95.70			
		Süleymaniye	0.37	1.14	0.24	2.94	111.47			
		Idealized Sample	0.55	2.20	0.20	3.99	101.59	66.44	105.35	138.28

C - A critical review of the heat energy demand modelling

As explained by Erhorn (2007), when modelling energy consumption of real buildings, a major question for the modeller is the fair balance of the complexity and comprehensiveness of the model on one side and the available quality of input data and the use of the model results on the other. When assessing energy consumption for buildings, the quality of the input data is still a major problem and often underestimated. This requires frequent revisions of dynamic models when applied to real cases and when aiming to assess the real energy consumption.

This problem is even more accentuated at the neighbourhood or city-wide level. Here, the input data is an even greater problem and often may not be available, requiring various advanced statistical methods to generate datasets. As a consequence, more simplified model are often used which lead to less exhaustive, but at least more reliable results.

For this study which included a dataset of around 30 million sqm in total, a static model was chosen to calculate the annual heat energy demand as a theoretic value. It did not aim to produce real energy consumption values. Instead, the central question was about the relative effect of urban morphology on heat energy demand from a purely comparative perspective across the 120 samples, a task for which a static model offers a suitable level of simplicity. No doubt, a model that takes into consideration the monthly or hourly climate approach following EN ISO 13790 would give more detailed results and can easily be integrated as part of follow-up research, where a range of different questions can be analysed in more detail.

A further constraint for interpreting the results from common modelling approaches, is the choice of selecting a base scenario, which includes a range of building parameters that were set constant. The aim of standardizing values that in the real samples are actually quite different simply helps with the comparativeness of the calculated heat demand across the different case studies. The values were chosen based on a subjective assessment of the average performance data for historical and modern buildings while reflecting the main characteristics of the sample.

For example, the ventilation ratio is closer to a mechanical ventilation standard. Generally, the distortion is much accentuated in older buildings, where air tightness is not ensured and the ventilation ratio can vary by up to a factor two in older or low standard buildings. This is the case for the traditional urban block, whereas in modern tower blocks, higher losses might be caused by higher exposure to winds, leading to higher penetration. In such contexts, the behavioural attitudes of residents and the availability of mechanical ventilation can considerably impact on the final results.

Furthermore, the method to assess thermal bridges was simplified, as the same construction standard was assumed across all samples. The effect of losses through thermal bridges was set as 5 per cent over the total losses of the facade, while the actual heat dispersion caused by thermal bridges can be twice as high.

Also, glazing ratios need to be considered more carefully. Most buildings have a glazed surface which covers between 20 to 25 per cent of the facade surface, reaching peak levels of 35-40 per cent in normal stone or concrete buildings. In the heat demand assessment this leads to a higher impact of the heat gains through solar radiation. Having chosen a u-value which represents double glazing standard, the effect on the heat losses is still noticeable, but if the standard would be set to passive house or low consumption house standard, glazing can be increased further for access to daylight while heat losses are minimized

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