URBAN FORM AS AN ENERGY MANAGEMENT PARAMETER

Futcher[1], J.A., and Kershaw[2], T.

1 Urban Generation, Islington London

2 Dept. of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, UK

ABSTRACT: Urban form is generally economically driven; as a result little attention is paid to how the surrounding urban geometry affects the energy performance of a building. Instead building designers tend to rely upon a fabric first approach to energy management. This work explores the interdependent relationships that develop between buildings at the scale of the city street. We use dynamic thermal simulations of multiple buildings at the scale of a neighbourhood to study the effects of urban form on the regulated loads of modern non-domestic buildings. Simulations are based upon the area of Moorgate within the City of London with simulations of buildings in their standalone setting are compared against identical buildings in various urban settings, both for the current climate and a possible future climate within the lifetime of the building. In this way the effects of urban form were compared to the effects of improving the building fabric. We find that not only do identical buildings behave differently as a direct response to the form of the surrounding urban setting, but that these performance patterns become increasingly significant with lowered operational loads (as a result of the mitigation agenda) and predicted warming trends. The results imply that the current fabric first approach to meet carbon reduction targets and avoid dangerous climate change may not be adequate.

Keywords – building form, urban climate, energy management.

1. INTRODUCTION

The series of UK government commissioned reports, titled ‘Zero Carbon Non-domestic Buildings’ (AECOM, 2011) included an investigation into the role of building form as an energy management parameter. The findings of this research found that whilst the form a building takes has an influence on its energy management, the influence of this parameter can be overlooked on several counts;

- form is ‘economically’ driven
- energy savings can be made elsewhere i.e. through the building fabric

However this research assessed the role of building form under current UK methodologies that fail to recognise that identical buildings perform differently as a result of differences in the surrounding urban setting that is a current generic ‘fabric’ first approach which misses valid energy management opportunities for current and future urban scenarios. Whilst there have been various comprehensive studies that have evaluated the significance of the form of the surrounding setting on building performance, few have examined the interdependent relationships that develop between buildings at the scale of the city street (Futcher et al. 2013). Recent research projects have explored the relationship between urban form and the urban heat island (e.g. LUCID and SCORCHIO) but largely the relationship between urban form and building energy consumption has gone unexplored.

Under under the framework of climate change and sustainable development of the UK Climate Change Act 2008 the UK govenment has set a legally binding target of an 80% Greenhouse Gas (GHG) reduction by 2050 on the 1990 baseline year. The objective of this work is to explore these interdependent energy relationships and to highlight the importance of building and urban form as energy management parameters to see how they can aid building energy management in reaching these targets. Here these relationships are investigated through a series of thermal modelling studies that are concerned with the difference in regulated loads of modern non-domestic building types in their standalone setting (i.e. with no shading or radiative exchange from surrounding buildings) and against identical buildings in various urban settings. All buildings are defined by their form, and the form of the street in which they are placed. Here the form of the streets is defined by the established daytime urban climate parameter and the mean building height (H) to street width (W) ratio. All buildings are assigned typical building parameters, which include operational and activity loads associated with the timing of the building function.

The Dynamic Simulation Modelling (DSM) tool Integrated Environmental Solutions Virtual Environment (IES<VE>) was used here for its ability to simultaneous simulate multiple buildings (critical for evaluating urban form dependent performance of building groups), and for its efficiency in allowing changes to the both the regulated and operational loads to be made without having to re-run the solar calculations, a time consuming process, especially for urban or street scale simulation runs. Whilst IES <VE> can determine the annual heating and cooling loads based on input data such as building fabric, location and climate, these tools are currently limited in their ability to accurately represent many microclimate effects. For example, these tools cannot calculate the effect of urban morphology on changes to external air temperatures, anthropogenic heat gain to the urban system, or account for micro-scale effects such as decreased turbulent transport. Modelling of microclimate effects specifically related to an urban environment is dependent on such effects being embodied in the data of the weather file selected for the analysis. IES <VE> like most building thermal simulation tools, allows modifications to the weather file to be made, however the weather file is a predetermined parameter that cannot be modified as a result of the presence of a building or a group of buildings. In general, these limitations restrict studies to modified radiant exchange (direct and diffuse) on internal temperatures only.

Whilst these tools provide a realistic description for the calculations of shadowing, diffuse solar radiation and a limited level of solar reflection, they simplify other parameters for example ground reflectance, and surface temperatures, where surface temperatures of the surroundings (non-active elements) are the same as the external air temperatures. Solar radiation is intercepted and reflected by structures/surroundings and the ground plane in the model, however, only active elements within the model absorb solar radiation and exhibit a change in surface temperature and are capable of reradiating heat (infrared radiation). The solution is to simulate several buildings at once (as active elements) and allow the surface temperatures of the urban setting to be handled dynamically by the simulation tool depending upon the physical properties of the surface (i.e. solar absorbance, infrared emissivity, conductance and thermal capacity). In this way a street canyon within the model can exhibit the radiative exchange between buildings found in urban areas. The convective heat flux of the urban surfaces is correlated with the wind speeds and dependent upon terrain type (a general parameter set within the tool). Convection is determined using the exposure and surface roughness of the selected terrain, but does not account for microscale effects such as the Venturi effect. In other words the convection coefficient takes into account macroscopic effects as a predetermined local scale effect, thus determining the rate of heat loss at the outside surface of a building. If wind exposure is set to urban terrain in the weather data settings, then a sheltering effect is specified. This parameter modifies the heat transfer coefficient and is correlated to the weather file and wind direction, speed & height above ground, alongside temperature and daytime radiation level, which in turn are connected to the indoor conditions by the surface heat balance.

However, these tools are recognised to perform accurately when measuring the effects of solar gain, making them particularly useful for buildings with a daytime function. These parameters make the use of a building model (as used here) to simulate an urban setting, this is more appropriate than using a microclimate model since we can interrogate and track energy flows within the buildings better than with dedicated urban climate tools. Whilst it is a recognised that many of the weather files used in these types of studies are inherently limited both in terms of the spatial coverage of a region and being based upon historical observations of weather, they however are also often recorded at a weather station outside of the urban area, where diurnal and seasonal climate patterns background climate conditions can be quite different than those found at building level in urban areas. It is the timing of these variations resulting from the urban setting that influence building energy performance i.e. day time solar access beneficial to daytime heating needs but detrimental to daytime cooling strategies (Krüger et al. 2010), alongside determining the strength of the urban heat island (UHI). Whilst the UHI is recognised to be beneficial to heating needs, it is also shown to be detrimental to night-time cooling strategies (Kolokotroni et al. 2006).

In the urban setting the level of incident solar radiation at the urban surface is determined by the level of masking by the surrounding solar obstructions such as other buildings, orientation (defined by street axis) and latitude. This relationship is dynamic, and depending on the season and time of day, other than at roof level, full solar exposure of any surface at all times is unlikely. The urban heat island arises from solar radiation and re-radiated heat bouncing back and forth between surfaces at building level (giving rise to the term street canyon). The temperature at the urban surface (canyon walls and floor) is dependent on the timing and magnitude of solar exposure as well as the surface materials; therefore, temperatures of individual surfaces in a canyon can vary significantly. As before, there are limitations in how many of the resultant urban climate effects can be considered in DSM tools.

To add to these limitations, within the UK, urban climate, as with the background climate, are shown to be following warming trends linked to global climate change. These climate change effects make reaching target CO_2 reductions more onerous. Within the built environment meeting this target will not only require a range of measures to reduce the consumption dependant on the building's fabric and conditioning systems (the regulated load), and operational loads (loads associated to the buildings function), but also consideration of the energy exchanges that occur at the scale of the city street and the interdependent relationships that form between buildings.

To take into account the influence of these interdependent relationships on air temperatures, two urbanised climate files have been used. To represent the current baseline and future climate conditions and represent the average weather and climate over that period. These climate files are test reference year (TRY) type weather files based on UKCP09 generated data weather sets for Heathrow (Eames et al. 2011): the 'baseline' climate based on the period 1961-1990 (1970s), which is used as the baseline for climate projections and; the climate forecast for 2050s based on the A1FI emission scenario sampled at the 50th percentile. The UKCP09 generated data does not fully represent the urban heat island (UHI) (Kershaw et al. 2010). As such it is necessary to modify the weather files to include an UHI. Measurements of the UHI for London for different seasons and under different weather conditions has previously been reported (Kolokotroni, 2008 and Giridharan, 2009) From these observations the sinusoidal diurnal heat island effect was added to the weather files, with the magnitude of this effect varying with season and cloud cover. Further details of this process can be found in Futcher et al. (2013), see figure 1.

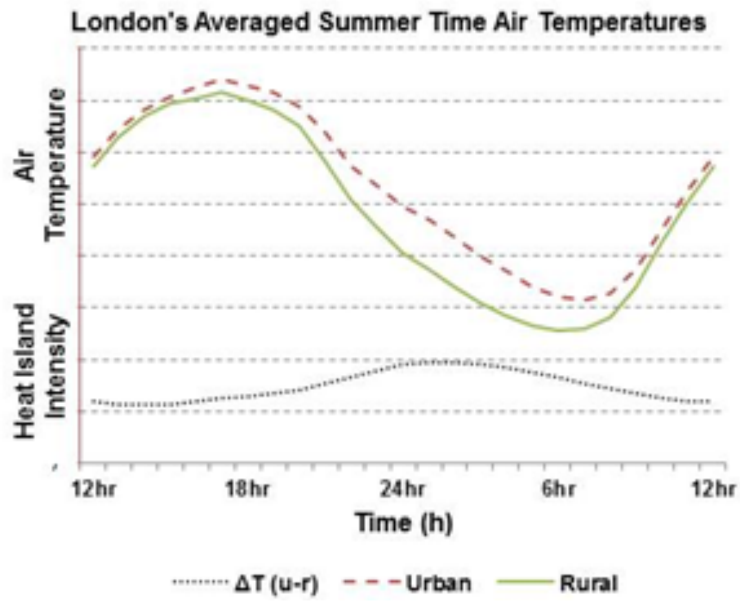

Figure 1. Typical diurnal variation of London's averaged urban and background dry bulb temperature, calculated from baseline weather files used.

As before even in a stand-alone setting, building performance patterns are subject to a vast range of variables that are associated with the regulated (the mechanically controlled systems and the building fabric) and operational or behaviour driven loads alongside the background climate. By taking a building from a stand-alone setting into an urban setting, these performance patterns are modified further as a result of the interdependent relationships between buildings. Therefore, to be able to evaluate the role of the urban setting, building performance parameters need to be defined, as shown in table 1. This study examines the influence of urban geometry and form on the aggregate energy performance of the adjacent buildings. It considers this for a typical London street of office buildings that are occupied during daytime and consist of glass-fronted office buildings along a north–south oriented street, Moorgate. These buildings are large open-plan office buildings over, seven floors above ground. They have a large glazed frontage, and face each other across a street that is 20 m wide and void of vegetation. The urban form that characterises this area generally consists of parallel rows of terraced office buildings of similar height arranged in a grid. In the model this building form is represented by Form A (Figure 2). Although external conditions are moderate, internal heat gains for this building type are significant and daytime cooling dominates. For this study the baseline period (1970s) energy performance of the buildings (individually and in aggregate) was compared to that for the target period (2050s).

Table 1. Building properties and Occupancy Profiles for the two form A and B, are taken from current guidelines and legislation

Building Properties	**Form A**		**Form B**	
Floors above ground	7		14	
Net Total floor area (m^2)	4000		4000	
Building Footprint (m^2)	600		300	
Building Height (m)	24.5		49	
Width (m)	10		10	
Length (m)	60		30	
Surface area front face(m^2)	1470		1470	
Surface area roof (m^2)	600		300	
Glazing (street face only) (m^2) (60%)	882		882	
Volume (m^3)	14700		14700	
Occupancy Profile				
7:30 am & 19:30 pm working week only, weekends are not included (holidays are treated as a working day)				
persons/m^2	0.1			
internal gains (kWh/m^2/yr)	Current a] 78	Future/low b] 47	1990 c] 59	Future/high d] 109
U-values (W/m^2K) - UK Building Regulations	L-1990		L2A-2014	
Flat Roof (Bitumen & stone chippings)	0.45		0.25	
External / Party Wall (Masonry)	0.45/ 0.2		0.35/ 0.2	
Floor	0.45		0.25	
Window	5.7		2.2	

Here two building forms are employed (labelled A and B) to represent typical building forms found in the UK (Figures 2-4). Both forms have identical floor areas, external glazing (on one façade only) and building envelope fabrication, but are distinguished by their footprint, building height and orientation, based on the direction of the glazed facade. The aim here is to identify performance patterns associated with both the building and urban form alongside the building fabric (regulated loads) and those associated to the building functions (operational loads) here represented by internal gains.

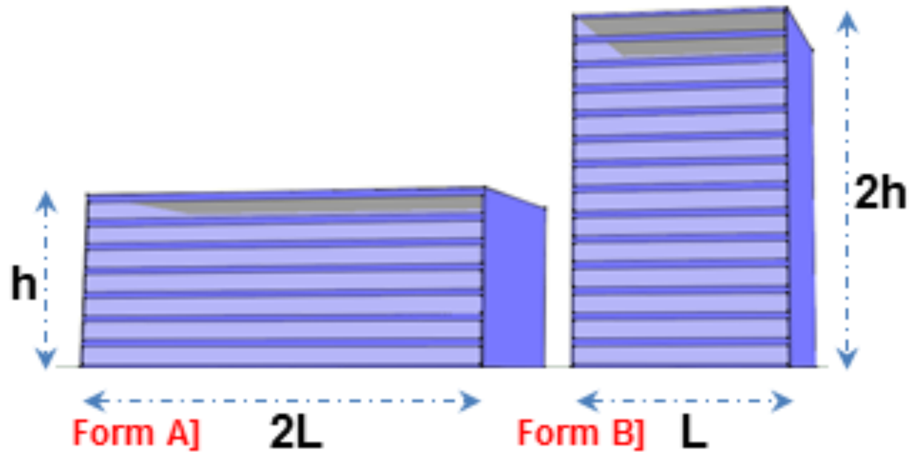

Figure 2. The 2 building forms (A and B). The difference is limited to Form A having twice the footprint of B, which has twice the height of A. Both forms have equal front surface and glazed area

For this study eight street canyons (C) representing a variety of realistic urban settings based upon the Moorgate area of London were created from the two standard building forms (A and B) arranged as two parallel rows (figures 3 and 4). These canyons are 240 m long and 20 m wide the glazed facade of each building faces toward the building opposite. Each of the canyons is oriented north to south so the individual building elements (A or B) are oriented east (E) or west (W), that is A-E (form A facing East), A-W, B-E and B-W. These canyons are placed within a larger street system such that each of these canyons are surrounded by other buildings that represent the urban environment. In figure 03 the darker buildings are those simulated in the DSM while the lighter buildings are there to provide boundary conditions.

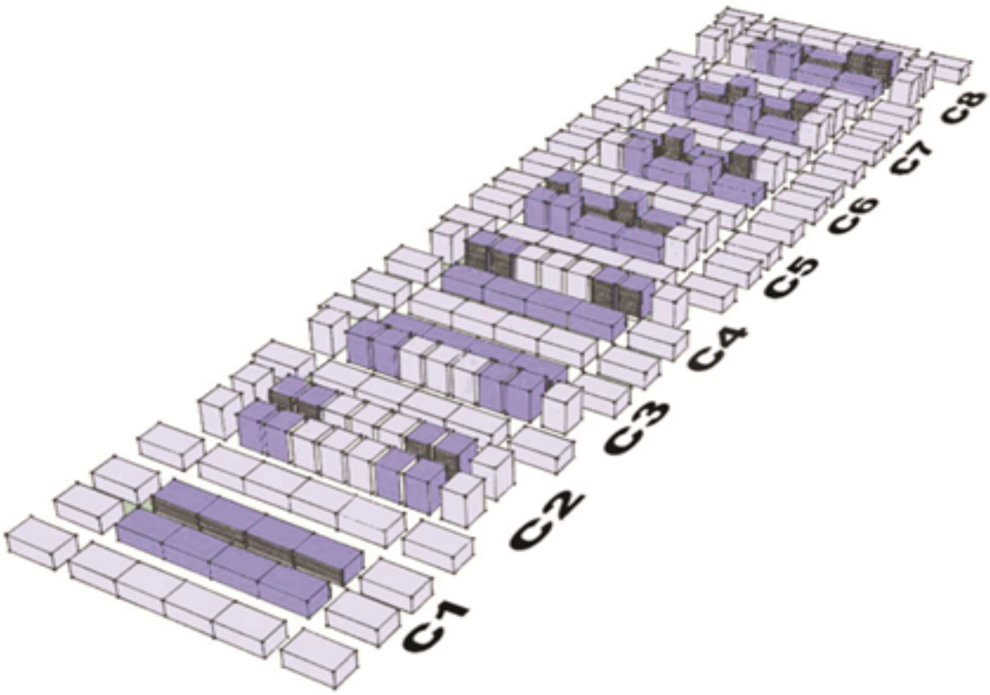

Figure 3. Geometric arrangement for the 2 Office building forms (A and B), in the 8 canyon configurations. Results are presented for the darker buildings, while the lighter building provide shading and radiative exchange.

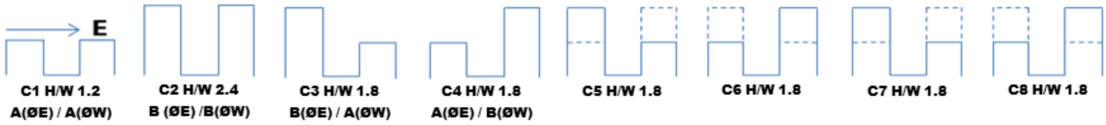

Figure 4. Section through the 8 urban canyon configurations

Current new build and/or refurbishment rates within the UK are estimated at around 2%, taking this into account it is clear the current 'fabric first' approach will have a limited effect on achieving the required net-target reductions (Futcher et al. 2013). Thus operational load management has been identified as a key strategy. Jenkins et al. (2007) shows that by lowering internal gains, warming trends can be offset, however the results point to an increased heating load (Jenkins et al., 2009a). Similar reductions in conditioning loads were also reported by Johnston et al. (2011), whereby the effects of internal gains on conditioning loads were investigated further. Future internal gain scenarios where shown to have a 'dual fate' that either decrease by a possible 56% or increase by 40% against current benchmark value of (78kWh/m^2/yr). The environmental impact of regulated and operational loads in terms of CO_2 emissions are based on electricity conversion factors of 0.52 kgCO_2/kWh and for gas of 0.19 kgCO_2/kWh for the baseline year, however for the target year all regulated load is provided by electricity; these are the current conversion factors used for compliance to current buildings regulations in England (Part L). In addition, a renewable fraction of 50% is included for the target year (Hubler and Loschel, 2013).

2. RESULTS

We present below the annual heating and cooling demands in kgCO_2/m^2/yr and kWh/m^{2}yr, and illustrate how these vary for the different urban forms under consideration. For clarity the results are also shown as a percentage difference when compared against the reference building. In addition, the results for the current scenarios represented here are in line with current UK energy benchmark guidelines for office building types (ECG 19 2000) and the measured annual energy consumption (Knight and Dunn, 2005).

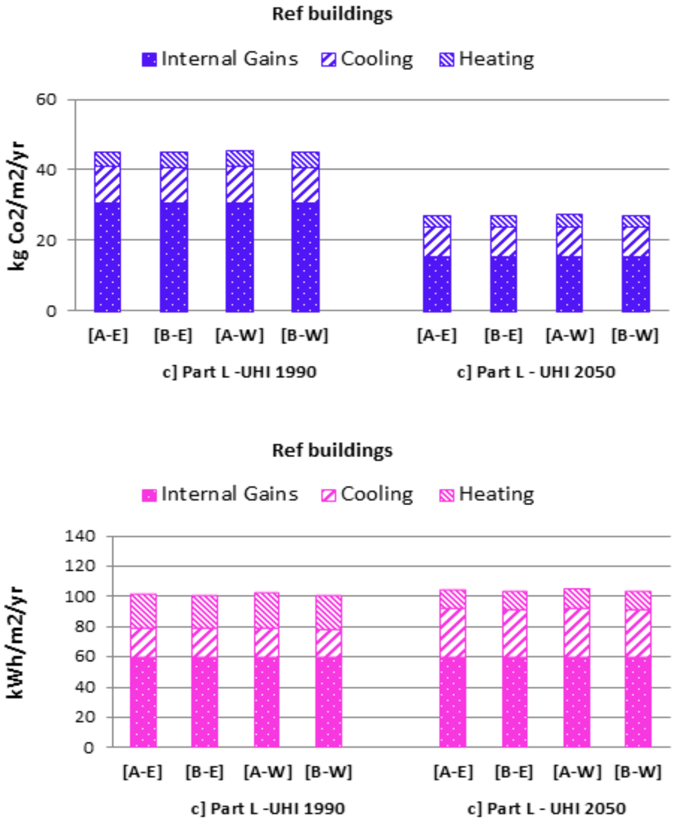

Figure 5. Ratio of demands (kWh/m^2/yr and kgCO_2/m^2/yr) for the stand-alone reference buildings – Forms A or B, (E and W) Ø, for both the baseline (1970s) and target (2050s) year urbanised climates – Building Fabric is to Part L 1990 and internal gains are to 1990 c]

Figure 5 shows the annual heating and cooling loads as kWh/m^2/yr and as kgCO_2/m^2/yr for the all buildings in their stand-alone setting for both the baseline and target year urbanised weather files. The results show the ratio of the energy demands for the stand-alone buildings for both for the baseline (1970s) and target (2050s) year urbanised climates. In these two scenarios both sets of building groups have been set up with, 1. the baseline year level of internal gains (59kWh/m^2/yr - c]) and 2. the baseline year building fabric (U-values Part L 1990). The results highlight several observations; firstly, that in a standalone setting, both building form (A or B) and/or orientation (Ø E or W) show little effect on overall demand, and that the role of these influences (form and orientation) are little effected by predicted urban climate warming trends. Secondly, that whilst the overall energy demand (kWh/m^2/yr) increases only slightly as a result of the predicted warming trends, the ratio of these demands alters (i.e. increased cooling loads and lowered heating loads for the target year (2050s) climate), and finally, that these demands are significantly lowered for the target year when translated into CO_2 levels. The variation in CO_2 levels results from both changes in the conversion factors (i.e. 2050 heating supplied via electricity rather than gas) and the 50% renewable fraction. However this heating load reduction could result from the reduction in U-Values. In addition, and a little more surprising, is that an improvement in building fabric (i.e. improved U-Values), only just offsets the influence of the warming trend, with very little effect to the overall performance. Any difference in demands that occurs between scenarios (scenario c] (i.e. baseline 59kWh/m^2/yr) part L UHI 2050 to scenario c] part L2a UHI 2050) results from the reduced heating load.

Again, as with figure 5 significant savings in CO_2 levels are as a result of the renewable fraction, and little variation between form and orientation is observed. Finally, the results demonstrate that internal gains are a significant driving force on building performance (Lam 2000; Voss et al., 2005 and Jenkins 2009). To investigate this further, various combinations of U-values and internal gains for the standalone reference building [A-E] (form A building oriented to the east) were simulated; windows and opaque elements were considered separately. For brevity figure 6 presents only results from [A-E] as these were found to be representative of all results. This is effectively an examination of the effect of building fabric improvement versus internal gain adjustment for a single building design. From these results some obvious conclusions with regard to the standalone building can be drawn, firstly all future scenarios result in a decrease in heating load which show a level of dependency on the building fabric, and secondly, that internal gains drive the cooling load. For these scenarios the cooling loads unlike the heating loads are not shown to be a fabric dependent load and if anything show an increase in demand when building fabric is improved. This highlights that reducing U-values can lead to increased instances of overheating and in the case of offices with cooling, increased cooling loads. This result is mirrored in a study by the National House Building Council (NHBC 2012), in that changes to building regulations and reducing U-values has lead to increased overheating risk in new build homes. The results between buildings within their internal gain groups (c] baseline year 59kWh/m^2/yr, a] current 78kWh/m^2/yr, b] future low 47kWh/m^2/yr and d] future high 109kWh/m^2/yr) all stay within the same range regardless of building fabric but show a reduction in the buildings representing the baseline year (both part L and UHI based on 1990 levels).

The results indicate that internal gains are a major driving force for building performance specially when considering the impacts of climate change and the UHI. These results suggest that lowering internal gains (loads associated with operation) is as effective as improved building fabric, if not more effective, in reaching target reductions against the 1990 baseline (c] part L UHI 1990), however none of the scenarios here reach the level of reduction required to meet target levels, around 10kgCO_2/m^2/yr. Figure 6 indicates that simply improving building fabric particularly for higher internal gains can have an adverse effect of space conditioning loads. The increase in cooling required can outweigh the heating savings. There is an interesting scenario where improving window U-values reduces heating requirement but has little impact on cooling loads where as fabric improvement increases cooling loads. This can give rise to the effect demonstrated by scenario c] where improvement to [L2A-L2A] 2050 (improved windows and building fabric) has had almost no net effect on space conditioning loads. In fact for the high internal gain scenario d] this has lead to an increase in overall conditioning loads.

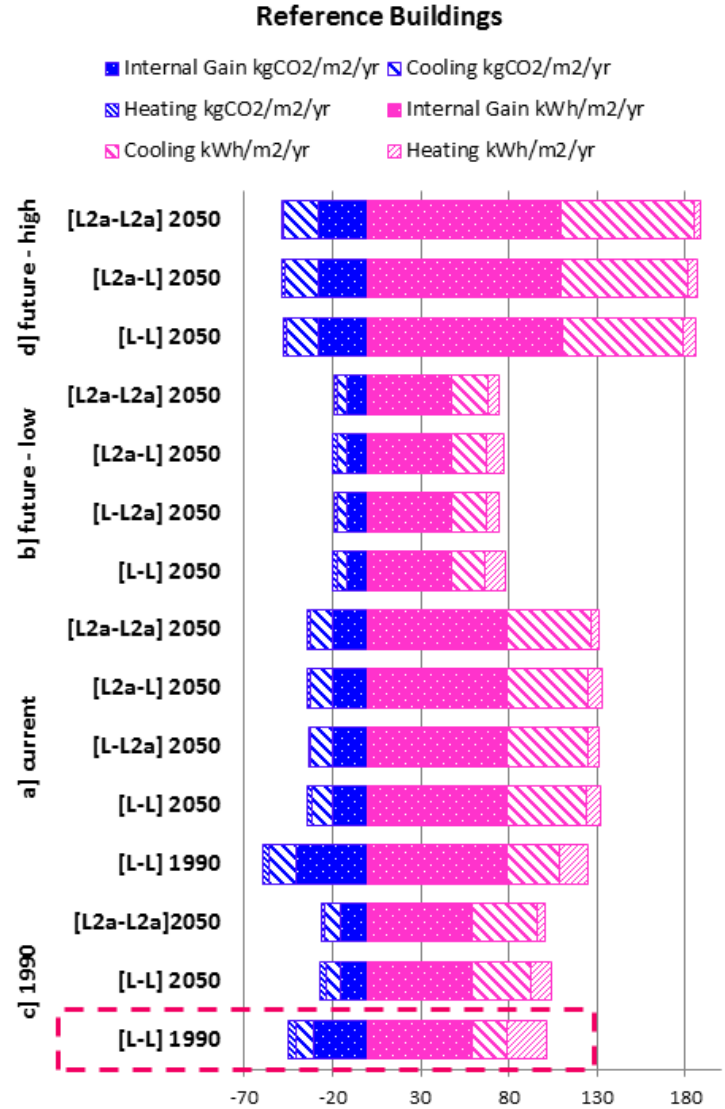

Figure 6. Ratio of demands (kWh/m^2/yr and kgCO$_2$/m^2/yr) for the stand-alone reference buildings [A-E] for the baseline (1970s) and target year (2050s) climates and for the 4 levels of internal gain. for example [L-L] 1990 is for a A-E with Building Fabric to part L1990 and windows part L1990.

It should be noted that these buildings are examined in a standalone or isolated setting where the influence of the surrounding urban setting on building performance is not taken into account. In the urban setting, the level incident solar radiation at the urban surface is determined by the level of masking provided by the surrounding solar obstructions (i.e. other buildings), orientation (defined by street axis) and latitude. This relationship is dynamic, depending on the season and time of day, whereby other than at roof level, full solar exposure to any surface at all times is unlikely. The temperature at the urban surface (averaged over the building or street canyon walls and floor) is dependent on the timing and magnitude of solar exposure, whereby surface temperatures of individual surfaces in a canyon can vary significantly. It is without doubt that these interdependent relationships, the relationship between urban form and the level of solar exposure, are significant energy management parameters in the urban setting. To demonstrate this the three future internal gain scenarios a], b] and d] part L UHI 2050 (78, 47 and 109 kWh/m^{2}yr respectively) are compared against the base line year c] part L UHI 1990 (59 kWh/m^{2}yr) in the urban setting to see the influence of the building and urban form on building conditioning loads (figures 7-9). Several different configurations of building forms A and B were considered for 8 different street canyons, which are shown in figure 3.

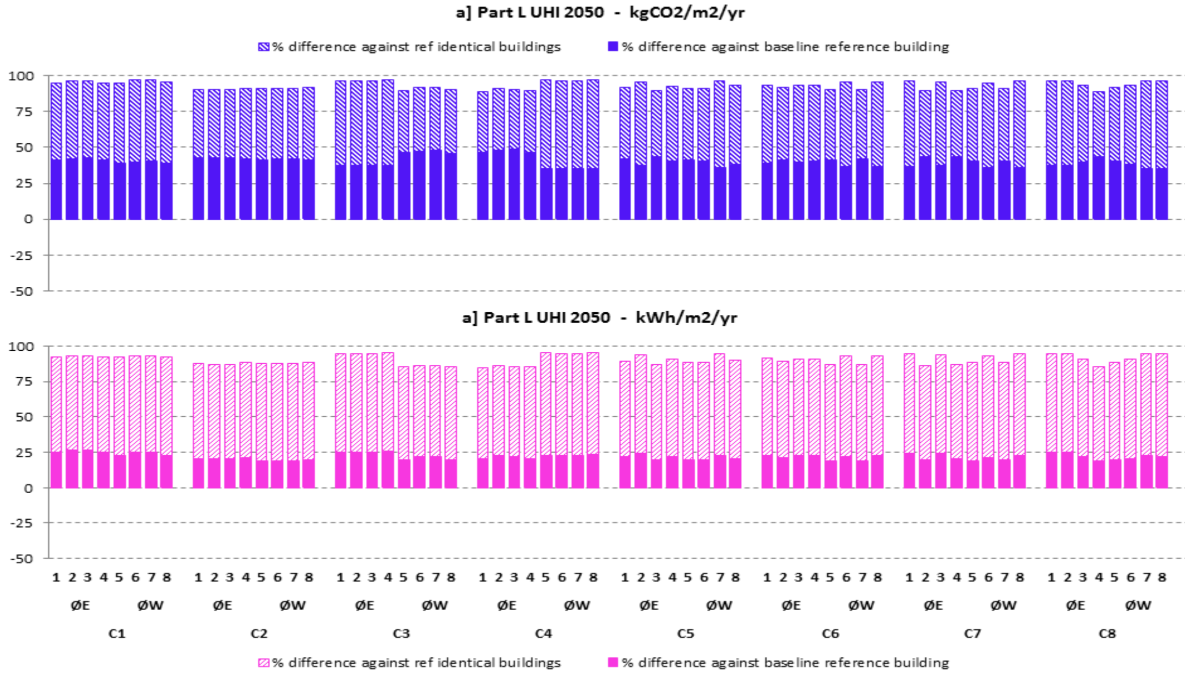

Figure 7. Annual space conditioning (heating and cooling) loads for the two building forms in different street configurations for the target year climate with current levels of internal gains a]. Results are shown as the % difference of all buildings in their urban setting against the identical building in its standalone setting (light shading) and the % difference against the identical building in their identical configuration for the baseline conditions c] (darker shading). Results are for both $kgCO_2/m^2/yr$ and $kWh/m^2/yr$.

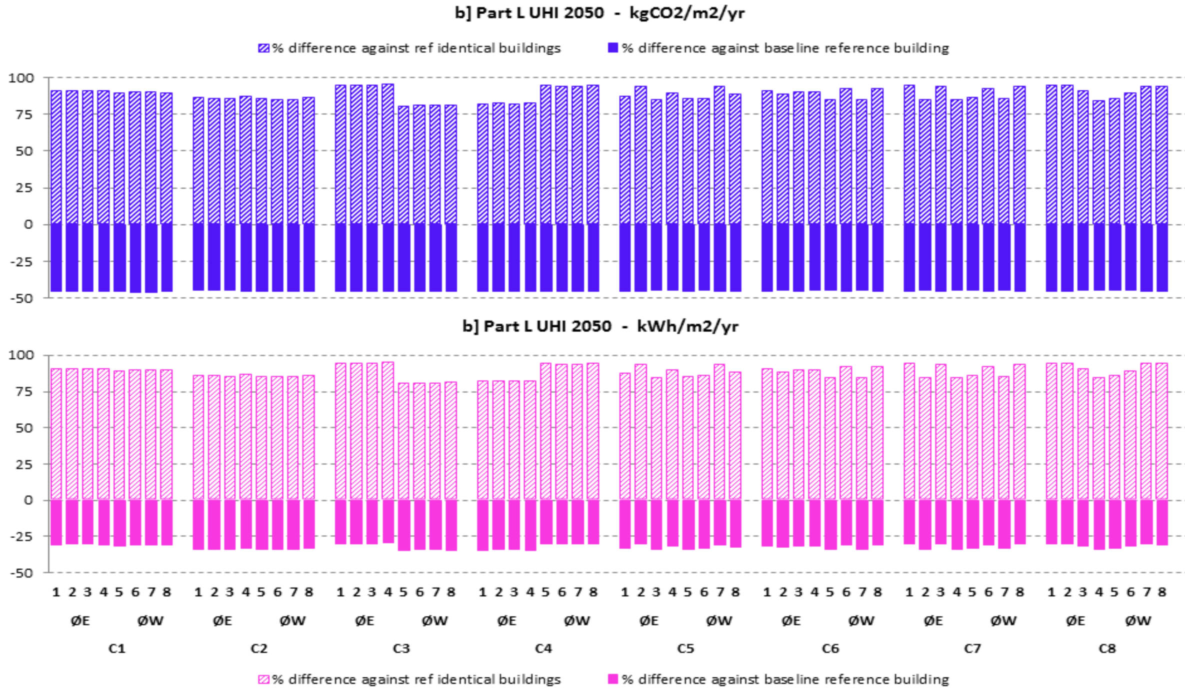

Figure 8. as figure 7 for low levels of internal gains b] (47 kWh/m^2yr).

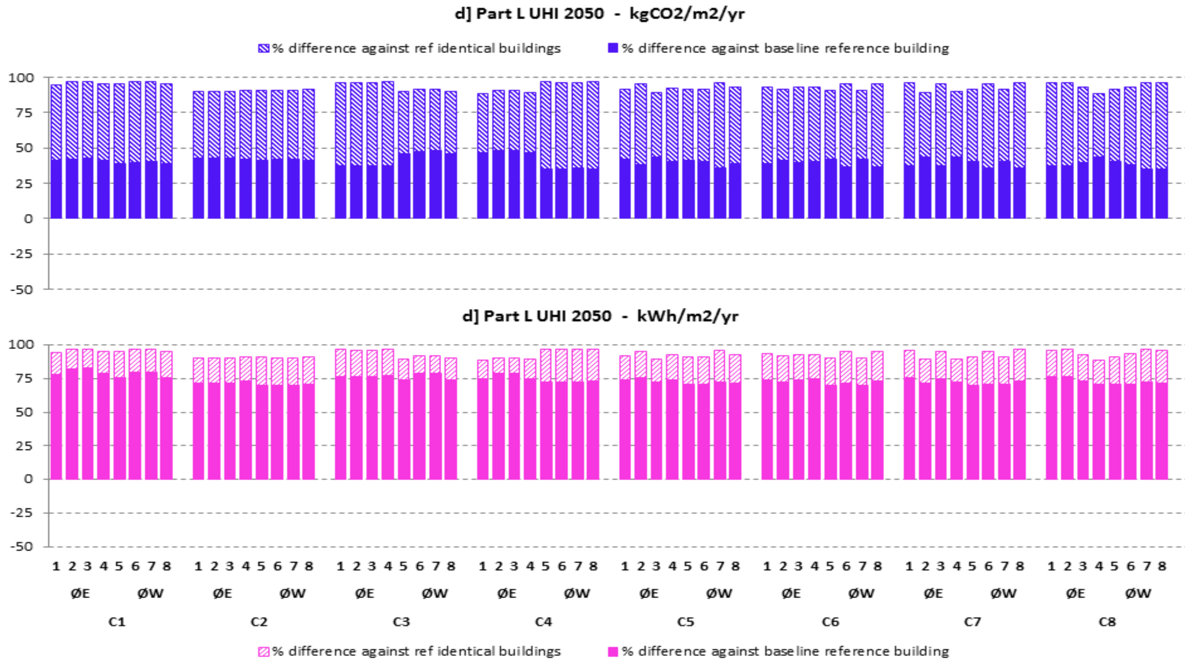

Figure 9. as figure 7 for high levels of internal gains d] (109 kWh/m^{2}yr).

From these 3 figures we can see that regardless of level of internal gains the form of the urban setting has an implication on building performance. All buildings display reduced space-conditioning loads in the urban setting compared to the standalone rural setting (lighter colour bars). This can be attributed to the fact that cooling load dominates over heating load (as shown in figure 6) and the increased shading of the urban setting reduces this load. As might be expected then scenario C2 (taller building form B) displays reduced loads compared to scenario C1 (shorter building form A) due to increased mutual shading. This effect is most apparent for the asymmetric scenarios C3 and C4, where the taller building form B is located on the West or East side of the street canyon respectively. The shorter building form A experiences dramatic reductions in conditioning loads compared to form B due to shading from low sun angles in the afternoon (C3) or morning (C4). Interestingly these simulations show little difference between morning or afternoon shading. The more complex configurations C5-C8 illustrate why consideration of shading in an urban setting is necessary to estimate conditioning loads. This effect is greater in the lower internal gains scenario shown in figure 8, demonstrating the greatest variation in space conditioning loads as a result of the urban setting. This implies that as we move towards a more efficient low-carbon society the effects of urban form will become increasingly important.

The influence of internal gains in the urban setting (darker bars) is complex. As shading from the urban from acts to reduce conditioning loads (particularly cooling loads) internal gains have an inverse affect acting to increase conditioning loads as internal gains become increasingly relevant to the building performance. One might expect this relationship to be reversed in a scenario where heating loads dominate over cooling loads. The data shown in figures 7-9 also hints at the complexity of the interrelationships between gains, building fabric and urban form. These performance patterns are reflected in both $kgCO_2$ and kWh. Finally the results clearly show the importance of managing operational loads currently overlooked in favour of regulated loads covered by legislation.

3. CONCLUSION

The results are in line with urban climate research, which shows the daytime surface and the near surface air temperature of an urban street within the urban canopy layer is directly linked to the background climate and urban setting. This work offers a new perspective on energy management at the scale of the city street by demonstrating that when building energy management is considered within the context of the urban setting, the overall building performance follows distinct performance patterns, which relate to both the timing of the various urban climate effects and the timing of the building function. In addition, the results show that the role of both building and urban form to become increasingly significant when considering future urban scenarios, including urban climate change, and demonstrates the significance of a 'form first' over the current 'fabric first' approach towards net-target reductions, especially when considered with lower operational loads.

The results above have implications for the design of buildings in streets that are suited to modern office buildings, in which the primary energy demand is for cooling to offset external and internal energy gains. If we are to meet current carbon reduction targets, then a more holistic approach needs to be considered in which the building form, function and urban setting need to be considered alongside the building fabric as mechanisms to reduce building carbon emissions.

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