

THE IMPACT OF THE URBAN FORM ON HEATING, COOLING AND LIGHTING DEMAND OF CITIES

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ABSTRACT

The impact of the urban form on the energy demand of buildings is difficult to quantify. Only very few software tools are available that calculate the influence of mutual shading of buildings and topography on the energy demand. Some dynamic building simulation tools consider shading situations, but are limited to calculations of a specified window surface area with a given horizon line and cannot be used to simulate an urban area. If lighting electrical energy is also considered, the simulations become more complex, as the sky models need to be realistically represented. As a result there is not much information available, how the total primary energy demand is affected by the specific urban form. In this work, generic urban forms have been classified with regard to their overall energy performance. For selected forms detailed simulations of heating, cooling and daylighting were carried out on a floor by floor level to consider precisely the shading situation from neighbouring buildings. The parameters chosen for the urban form variation include the site coverage (i.e. density), settlement and building typology (block structures, row houses, multi-family houses, high rise etc.), building age and thermal standard. To validate the different simulation tools used, a case study was carried out on the urban area Scharnhäuser Park near Stuttgart, Germany, where energy consumption data are available for the whole settlement of 10,000 inhabitants. For a given urban situation detailed energy simulations were carried out and compared with measured consumption data. The models were then simplified to represent a more abstract generic form. Using the geometrically simplified model, parameter variations were carried out, for example on site coverage, to calculate the impact of the urban form on the total energy demand. About 20% difference in energy demand was obtained for the same building typology, but higher surface coverage for a middle European climate with dominance of heating energy consumption. In the paper the different energy performance of urban forms will be compared for different climates with varying heating, cooling and daylighting situations.

KEYWORDS

Urban form, urban energy performance, heating, cooling, lighting.

INTRODUCTION

Energy efficiency and sustainable environments for cities have become a key topic of the recent studies. In order to evaluate the effects on urban energy performance, it is important to quantify relationships between wide ranges of urban factors. Urban design has a significant influence on energy performance of cities and it is irrespective of the socio economic context (Rohinton, 2005). To quantify the effect of this factor would be the first step for understanding the energy requirements of the cities and associated problems on environment and human health.

Urban spatial structures together with urban forms shape the urban structure design. According to climatic conditions the structure of the urban quarters and their surface properties may have a positive or negative influence on the lighting, heating and cooling energy demand of the buildings. In the different research studies daylighting or thermal performance were investigated for urban areas related to urban forms. To understand which urban form gives the best land-use according to daylighting availability was evaluated in the late sixties by Leslie Martin and Lionel March in Cambridge. They classified the urban forms according to their daylighting performance as pavilions, slabs, terraces, terrace-courts, pavilion-courts and courts. A range of studies according to the Martin and March classification on urban forms were made by Gupta 1987, Blowers 1993, and Steemers *et al.* 1997. Their works only considered the irradiance on the facade and does not include the work related with

daylight responsive energy demand. Their findings were obtained using an innovative analysis method (image processing techniques) and a real urban case study by Ratti *et al.* 2003. Steemers (2003) assessed the building geometry impact on lighting and thermal energy consumption and developed the LT Method which is used for estimating the energy usage of lighting, heating, cooling and ventilation for 30 design variables. When the LT method is combined with image processing techniques, it can be used for calculating energy properties of different urban densities. Eugenio *et al.* 2009 calculated heating and daylighting performance of six configurations of different urban blocks based on courtyard typology with the same method according to daylighting factor and daylight autonomy. They did not use ray-tracing or the radiosity technique, because of time consuming simulations and high level of detail. Mardeljevic and Rylatt (2000) used the ray tracing method for understanding the irradiation in complex urban environment. R. Compagnon (2004) produced irradiation results with a periodic solar radiation distribution method to determine the viability of passive and active solar energy technologies in the urban context. Kämpf *et al.* 2009 used the ray tracing method with a cumulative sky approach (Robinson and Stone, 2004) which worked with grid points on the surface of the sample buildings and received values for the total irradiation on the facade according to the sky obstruction. Also different simplified calculation procedures or detailed dynamic simulation models are used for thermal behaviour of buildings but these programs are not meant for the urban areas and all of them neglect the magnitude of the urban effect. The EEP model (Energy and Environment Prediction model, Jones *et al.* 2001) is using the individual building as a starting point and gives some estimation result for a group of buildings with different energy efficiency measures. Another relevant urban energy modelling approach is the Sustainable Urban Neighbourhood modelling tool (SUNtool - Robinson *et al.* 2007). It simulates the hourly urban energy, water and waste flows with a simplified dynamic thermal model, based on a radiation model, which calculates solar and thermal radiant exchanges for the building envelope with stochastic occupancy models. To understand the (simulation) results, a certain experience is required and the program needs modification of a lot of default values in case of a different location and building and system design (Vreenegoor *et al.* 2008).

In this work, the classification of generic urban forms is combined with the site thermal properties and the building types. The major amount of the building stock is based on the residential housing, so these investigations are focused on the energy properties of residential house stock, in order to understand the urban energy concept. For selected forms and typology detailed simulations of heating, cooling and daylighting for different parameters (site coverage, building age and thermal standards) were carried out on a floor by floor level to consider precisely the shading situation from neighbouring buildings. As a result this research gives the quantified detailed energy demand for different settlement types for urban designers and energy management planners, who then can estimate the energy demand of the different urban quarters without socio economic context.

METHOD

Simulation Method

The classification approach has been used for determination of the affects on urban energy demand. According to energy flow, the analysis is carried out on three levels considering occupancy, building and urban form. The analysis model for energy performance of the building is shown in Figure 1. After this classification, in order to evaluate the energy performance of the urban quarters, a settlement is considered as several districts. Those districts are classified according to their using types as residential, commercial or industrial. The thermal properties of these districts have been determined according to the thermal climate zones classification made by Stewart I. and Oke T. (2009). In this study, the urban areas were classified according to characteristic sets of radiative, thermal, moisture, and geometric properties.

The real urban texture is highly complex to compute with software. In order to limit these complexities some archetypes were defined and these simplified types are used especially for energy performance studies. In this assessment three generic urban types were chosen: pavilion, terraces and pavilion courts. These types are configured on the site with different densities. For the second level of data (building level), the building properties are defined according to typology made by Institute for Housing and Environment-Germany (IWU, 2003). The building stock was explored on the basis of energy demand properties. The building typology is based on the construction years of buildings. All residential building stock is categorized as single family houses, row houses, multifamily houses, large apartments and high-rise blocks. Each class is described by a representative building, in particular, typical values for the thermal insulation characteristics (area, U-values). The residential settlement types are configured as the pavilion settlement type of one family houses, apartment and high-rise blocks, the terrace settlement type of row houses and the pavilion courtyard settlement type of old houses. The building types can be seen in Figure 2.

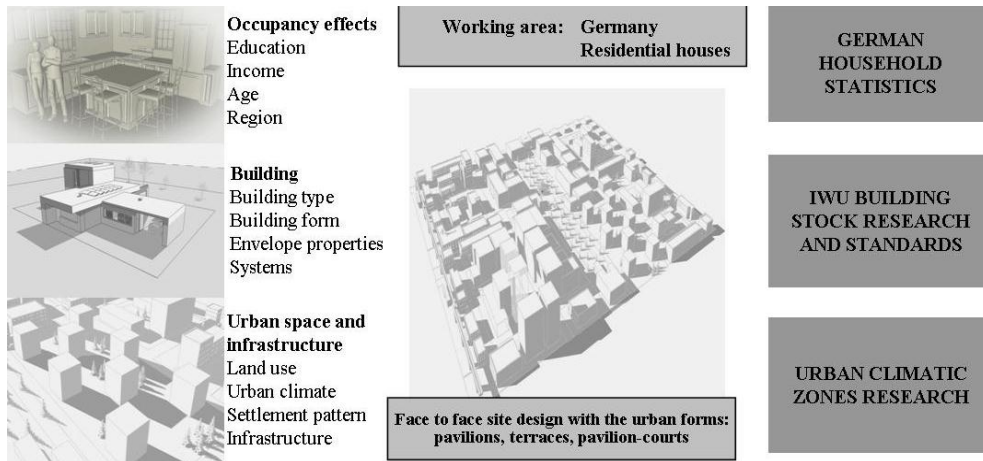


Figure 1: an analysis model for energy performance of the building

Three dimensional urban quarter simulation was done for different generic urban forms. The representative urban quarter constitutes of 9 generic building blocks from each building type and the distance between the buildings varies according to site density. The major orientation for the site design is the South. For the calculation of the floor by floor daylight illuminance the ray tracing program Radiance was used (Larson and Shakespeare, 1998). This study carries out daylight analyses and electricity consumption of daylight responsive artificial lighting for residential building spaces with different urban geometry configurations in different height level. Space configurations were evaluated in two types. The south façade window to wall ratio is 25 % and each space has 20% window wall ratio in the east and west facade. The daylighting performance has been analyzed using the so called useful daylight illuminance scheme. Nabil and Mardeljevic defined “useful daylight” based on a survey of reports of occupant preferences (Nabil and Mardeljevic, 2006). Daylight illuminances in the range 500 to 2000 lux are often perceived either as desirable or at least tolerable and called UDI autonomous (UDI-a). Mardeljevic also pointed out his work that accordingly, maximization of the occurrence of the UDI-a metric should be taken as the most reliable indicator (Mardeljevic, 2006). In order to compute internal daylight distribution, results were evaluated with daylighting metrics. The change is sensitive to building orientation and height of the floor. Annual UDI-a distribution of residential spaces can be seen in Figure 3. In the entrance floor level, the annual UDI-a of left building space (south and west oriented windows) is 35.82% and right building space (south and east oriented windows) is 33.42%. After the evaluation of daylight performance of two residential spaces, proper daylighting responsive artificial lighting system was designed. The space was equipped with artificial which provides 300 lux minimum illuminance in the space according to DIN EN 12464. Each selected 4 luminary power is 88W and total luminous fluxes of lamps are 4650 lm and efficiency is 61%. The annual electricity consumption with a daylight responsive control system was simulated in radiance based on the lighting program Daysim (Reinhart, 2006). To see the total energy demand of the building, heating and cooling analysis including the annual electricity consumption with daylight responsive control was calculated in the Energyplus simulation program (Drury C. B *et al.* 1999).

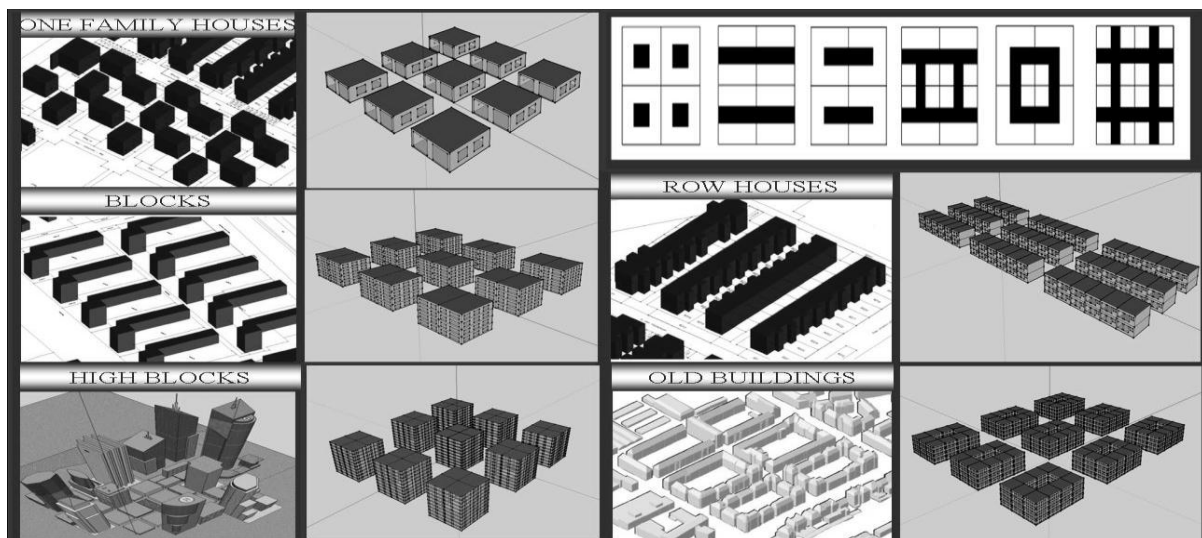


Figure 2 residential settlement types with face to face design according to building type

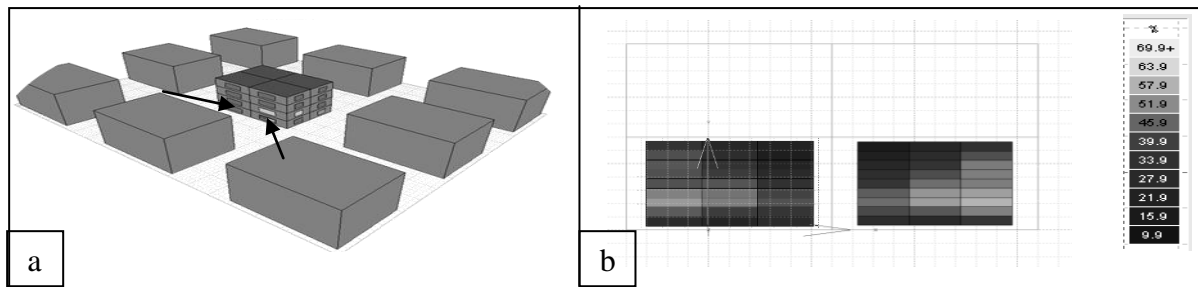


Figure: 3a.residential building spaces with south-west facades and south east facades 3b. Useful daylight illuminance autonomy performances comparison on the entrance floor working level (80cm height)

The classification of urban settlements traditionally relies on their population and activity type. While these descriptions might be appropriate for estimating the energy intensity of the area, they convey nothing to calculate the energy demand of the area. In this simulation, the German statistic data and measurements from site were applied for estimating the occupancy scenario. According to that, all types of residential buildings were simulated for one identical family scenario. The scenario is based on a family with 4 people and all of them do not use the flat during daytime except at the weekends. The usage time of the appliances was configured according to the statistic data related with German appliances. Every house is equipped with a television, computer, washing machine, dishwasher, oven, fridge, and microwave. The usage was determined as the average time taken from the German household statistic (Gruber and Schlomann 2005). The occupants were defined as seated and light working and the EN ISO 13791 numbers were taken as an input for internal gains from occupants. 40% of lighting energy were considered as convective gains. The heating set point is 20°C and cooling set point is 26°C. The heating system is shut down between end of April and October and vice versa the cooling is shut down from October to May.

Simulation validation with measured Data

Performing sets of experiments is important in order to develop a reliable methodology for assessing the urban effect on the measured energy performance of the residential buildings. To quantify the impact of the surrounding buildings on the energy performance of the case building in the urban context, daily measurements of heating and electricity consumption were taken from the case study area in the Scharnhäuser Park. The Scharnhäuser Park is geographically located at 48°68'N latitude and 9°21'E longitude and it is approximately 8 km southeast of Stuttgart, Germany. The Scharnhäuser Park currently has 7000 inhabitants and at present 80% of the energy demand is supplied from renewable sources. The supply system is fed by a 6.3 MWth wood fired co-generation plant which provides electricity and heating energy to the site. The Scharnhäuser Park is 150 hectares and the site offers the opportunities of public spaces, 40,000 m² of industrial area and 90,000 m² of commercial area and a wide range of housing types; apartments, residential tower blocks, row houses. In this study, 10 single family houses from Scharnhäuser Park were measured and simulated. Site plans and 3D drawing of buildings are shown in Figure 4.

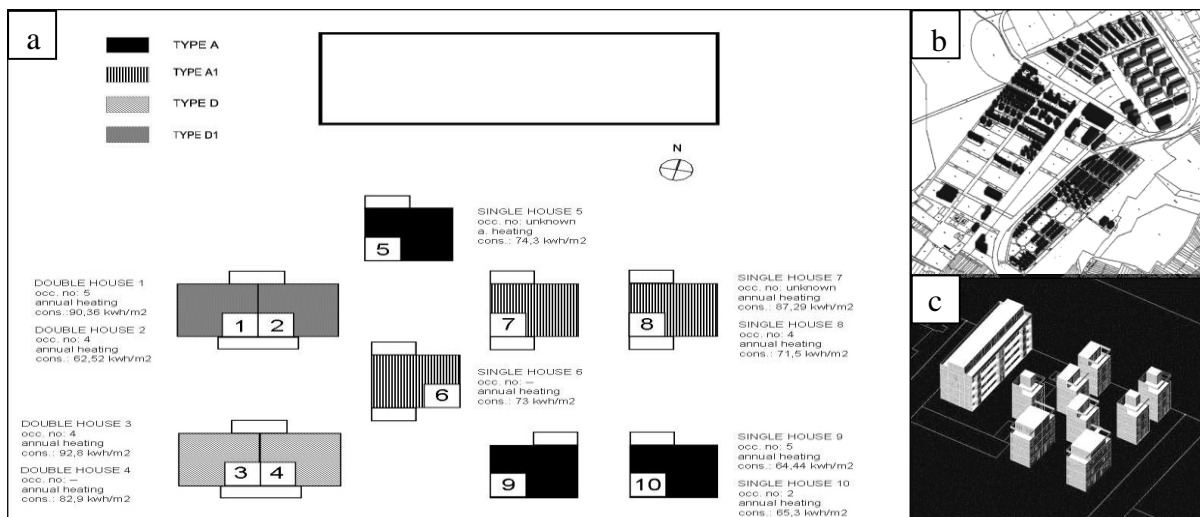


Figure 4a The location of 10 case study buildings and their properties. Figure 4b The case study area in the Scharnhäuser Park settlement. Figure 4c 3D drawings of the case study buildings

Table 1. The simulation sets for EnergyPlus calculation

Use of Building: One family houses				
Daily profiles: 5 People:2 parents and 2 children and 1 elder people. 1 person is whole day at home 4 or less People: The house is not occupied between 9:00 and 17:00 at weekdays				
People internal gains:120W/person(daytime-light working),100W/person(sleeping)				
Infiltration maximum flow: 0,2 h ⁻¹ (air exchange)				
Auxiliary ventilation: natural ventilation maximum flow: 0,6 h ⁻¹ (air exchange)				
Construction details	U value (W/m ² K)	Thickness (m)	Reflectance (-)	Visible light transmittance (-)
Exterior Walls	0,23	0,34	0,3	
Roofs	0,23	0,35	0,3	
Wall under the ground	0,36	0,35	0,3	
Floor under the ground	0,35	0,31	0,3	
Windows	1,23	0,04		0,55
Door	1,98			
Heating set points time schedule			Cooling set points time schedule	
Monday-Friday	00:00- 06:00 = 15 °C 06:00- 22:00 = 20 °C 22:00- 24:00 = 15 °C		Monday-Friday	00:00- 07:00 = 32 °C 07:00- 18:00 = 26 °C 18:00- 24:00 = 32 °C
Summer Period	Off		Winter Period	Off

The detailed simulation for evaluating the urban shading effect has been done for “Building 6” which is located in the middle of the site, so that the other buildings on the site cause a shading effect which increases the heating demand. The shading effect of one another building was defined in EnergyPlus with three dimensional site model and EnergyPlus calculates beam and diffuse solar radiation that is reflected from exterior surfaces and then strikes the building. For the energy plus model the energy consumption data for many residential houses were collected from monthly energy readings and for some specific cases they were measured with smart metering system. Daily electricity consumption for summer and winter season was evaluated according to weekend and weekday’s conditions and typical weekly summer and winter electricity consumption was defined. According to this consumption and daylighting simulations, the building equipment schedule was defined for the area. All buildings on the site are then calculated with the monthly energy balance model which is used in the planning phase of building to get the construction permit. The same design sets are used in the simulations with different air change rates and heating set temperature for houses according to different user scenarios. The simulation sets for EnergyPlus calculation is shown in the Table 1. When comparing measured and simulated results with dynamic simulation tool with Energyplus, which is shown in Figure 5, it is not possible to separate the shading effect from the user behaviour effect, which clearly dominates consumption. In the building detailed simulation, the building energy consumption and simulated values are quite close in most cases. The monthly energy balance results are always lower than the dynamic simulations.

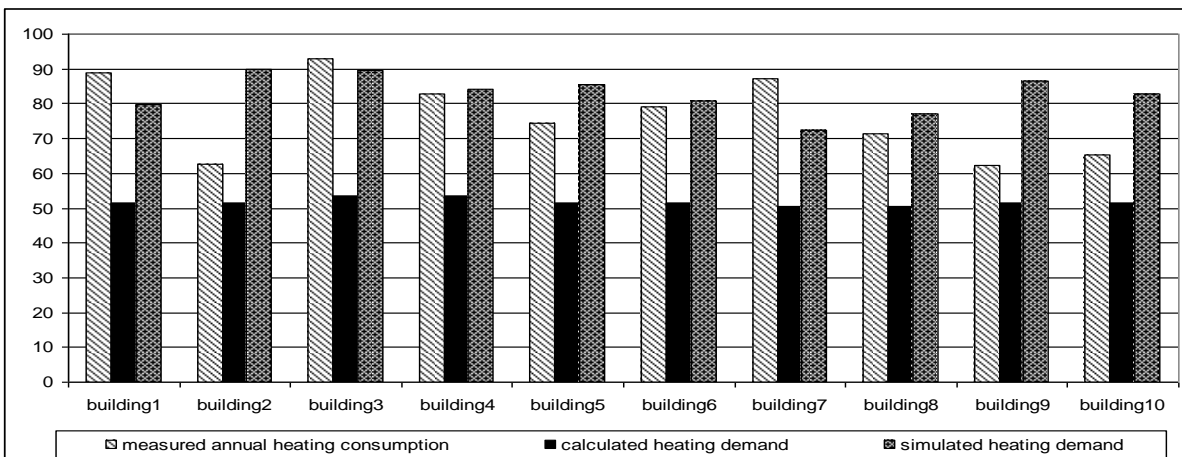


Figure 5 Measured, calculated and simulated heating demands for case study area.

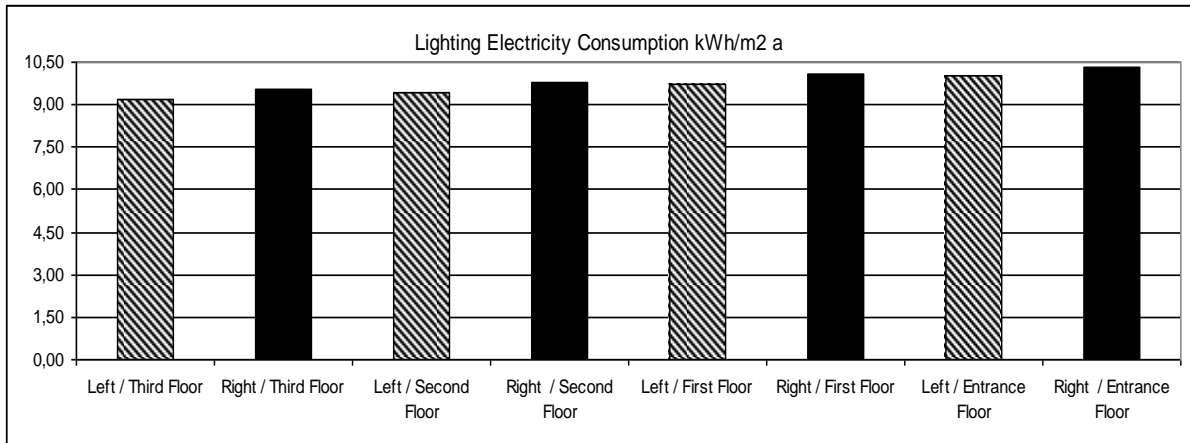


Figure 6: Lighting demand as a function of floor level and position of each apartment in the case study area with 40% site coverage.

RESULTS AND DISCUSSIONS

Lighting electricity consumptions calculations were done using the following daily schedule. Between 08:30-18:00 the space lighting system works with daylight responsive system, between 18:30 – 22:30 artificial lighting systems works at 75% of installed power, which reduces to 25% between 22:30 and 24:00h. It has been observed that the useful daylight illuminance autonomy tends to increase in higher levels of the building. Figure 6 represent the sensitivity of the electricity consumption with respect to orientation and building level. Floor by floor analyses results in approximately 10% electric energy saving between entrance floor and last floor. Figure 7 shows the heating and cooling demand of a one family house and apartment blocks in different dense areas which were constructed in between 1995 and 2001. Without any shading effect the heating consumption of one family house is 72 kWh/m² and depending on the shading of the area the heating consumption can be 17% higher than the buildings which are simulated without surrounding. When albedo is 0.7 for the surroundings with actual glazing areas, the heating demand of one family house is 79 kWh/m² in the 60% site coverage. The energy demand per square meter of apartment blocks is less than one family house. The heating consumption of the apartment blocks is 43.7 kWh/m² and cooling demand is 11.3 kWh/m². Depending on the shading on the site, the heating demand can be 18% higher more.

The heating consumptions of row houses are changing as a function of the total heated surface area to the surface area exposed to the ambient condition. The heating consumption of corner houses are 17% high than the other buildings in the middle of the row as shown in Figure 8a. Depending on the density on the site, the heating demand increases 11-13%. The reflection effect with density does almost not influence the heating demand of the row houses. The figure 8b shows the heating and cooling demand of the old blocks within the courtyard urban form. The old house has an very high overall heat transfer coefficient for the building envelope.

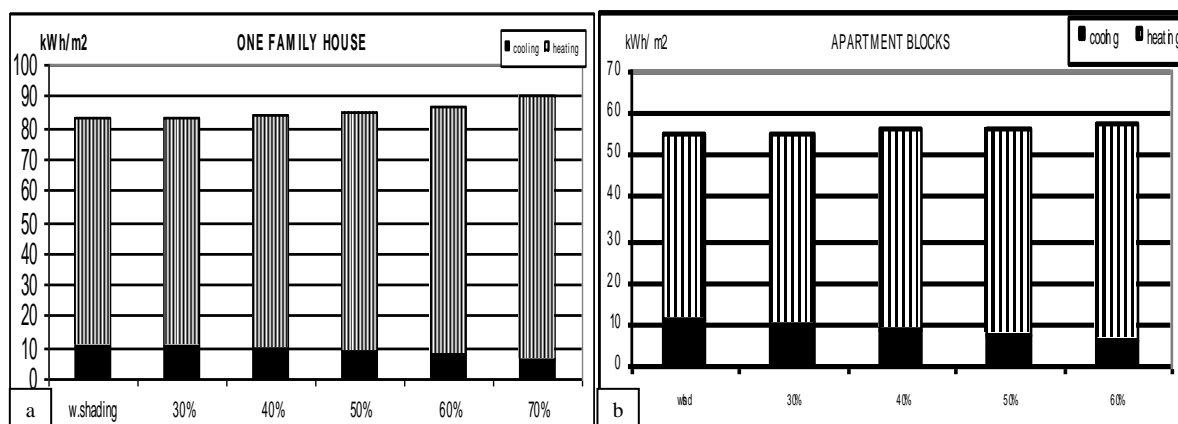


Figure 7a Heating and cooling demand of a one family house for different settlement densities in Stuttgart climate, 7b Heating and cooling demand of apartment blocks for different settlement densities in Stuttgart climate.

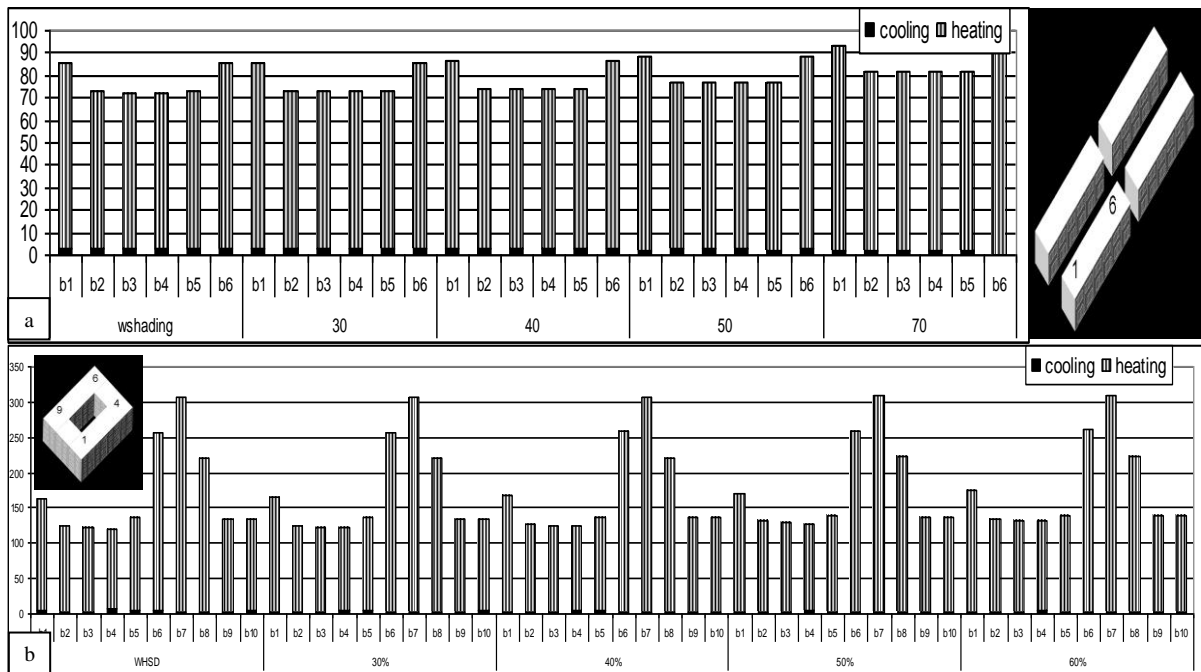


Figure 8a Heating and cooling demand of row houses for different settlement densities in Stuttgart climate, 8b Heating and cooling demand of old houses in the courtyard urban form for different settlement densities in Stuttgart climate.

The apartment blocks and the high-rise blocks are simulated for Stuttgart and Hong Kong climatic data (Figure 9). The dominating building energy demand is cooling for Hong Kong climate. In Hong Kong, the high rise residential blocks are very common in residential areas and the density of these blocks highly affects the cooling energy demand. The cooling demand of a well insulated high-rise block with 54 kWh/m^2 decreases to 37 kWh/m^2 with 60% site coverage in the Hong Kong. As a opposite of this, a heating demand of 53 kWh/m^2 for high-rise buildings in Stuttgart increases to 67 kWh/m^2 with increasing site density.

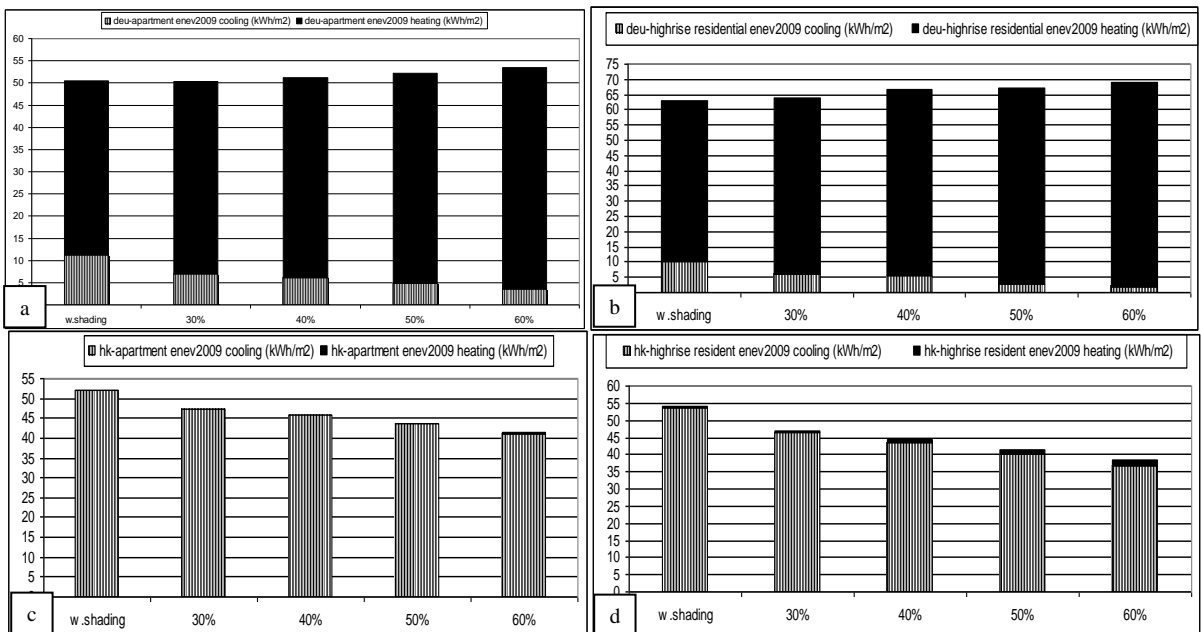


Figure 9a Heating and cooling demand of apartment blocks with U-value according to EnEV 2009 for different settlement densities in Stuttgart climate, 9b Heating and cooling demand of high-rise blocks with u-value according to EnEV 2009 for different settlement densities in Stuttgart climate, 9c Heating and cooling demand of apartment blocks with u-value according to EnEV 2009 for different settlement densities in Hong Kong climate, 9d Heating and cooling demand of high-rise blocks for with u-value according to EnEV 2009 different settlement densities in Hong Kong climate.

CONCLUSIONS

The presented paper shows exemplary results of simulations and measurements which aim to investigate the effects of urban structure and building forms on the energy performance of the urban quarters. This part of the research aims to carry out quantified lighting, cooling and heating energy demand calculations for different residential urban quarters.

The building construction and envelope design is very important in means of energy conservation, but first of all for the site design the possible solar gains should be investigated. Many aspects of the urban design, from the layout of the roads to the building shape will crucially affect the energy performance of the buildings. According to the dominant climate an energy efficient site design is very supportive for energy conservation in the building sector, in order to plan and manage resources to secure their long term use and continuity. At the earliest stage of the design, the decisions related with the site structure to use less energy, either by using more efficient technologies gives the best option on the energy management of the site. It is usually possible to ensure that the majority of buildings on a site are orientated to have good solar access for daylighting and reducing the heating demand. Optimized shading devices may be used for reducing the cooling load in the summer period. For summer dominated climate conditions, the site design can be helpful to reduce the cooling load, but in design phase also the daylighting situation and the lighting loads have to be considered. Combined detailed daylighting analysis and dynamic thermal simulations show, that 10-20% heating and cooling demand may be saved by an energy aware site structure. When we consider the used primary energy, the lighting and the thermal energy demand should be investigated together and the overall energy consumption optimization for operating the building has to be considered.

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