GIS-Mapping the Building Heating and Cooling Energy Demand for the City of Stuttgart, Germany

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Abstract: This paper introduces the research project KLISGEE. The goal of the project is to quantify the consequences of the urban environment, in particular the urban climate on the energy demand of buildings. The method applied combines i) numerical modelling by means of TEB and TRNSYS based on a DOE design of experiment plan, ii) statistical analysis for pre- and post-processing of the data and iii) GIS-mapping of the results. Much information is required, including long-term weather data, urban climate maps, geometrical city maps in high resolution, statistical data about buildings, traffic and people, etc.

Keywords:

climate change, urban climate, building energy demand, numerical simulation, TEB, TRNSYS, GIS

1. Introduction

Cities worldwide experience harmful gas emissions and heat release from buildings, transport and other urban activities which lead to the formation of urban climates, mostly characterized by urban heat islands (UHI). This urban climate boundary condition must be taken into account in energy-related simulations of buildings.

This research further builds on a previous research partly published see e.g. Ali-Toudert [1] [2] [3], which investigated the role of urban climate on the energy demand of urban buildings for different urban densities, building constructions and climate types. The present research combines similarly TEB and TRNSYS modelling tools and statistical pre- and post-processing using the DOE method. Additionally, it integrates practice into the theories, which were previously highlighted, and show its applicability on a real case study, i.e. the city of Stuttgart.

2. Methodology

The method used in this study is based on i) numerical modelling, ii) statistical methods and iii) GIS techniques. The successive steps of the investigation methods are illustrated in Figure 1 presented below.

I. Data sources and data processing

Three sources of climate data were considered to be used: i) measured weather data statistically interpolated on a resolution of 1 km generated by the climate-model LARSIM[1] [4], ii) weather data sets generated from atmosphere modelling for a 30 years period (1971-2000)[2] and iii) measured weather data from 3 weather stations[3]. Before the weather data are used as input of the simulation, they must be controlled to ensure their reliability and analyzed in order to clarify the climatic situation of the city Stuttgart, e.g. the spatial difference in urban local climates and microclimates.

The city data include i) 2D and 3D digital city maps with a 0.3 *m* and 5 *m* position and height accuracy respectively[4]; ii) statistical data of residential density[5]; iii) traffic data of Stuttgart. The 2D and 3D digital city

[1] Data are provided by Landesanstalt für Umwelt, Messungen und Naturschutz (LUBW).
[2] Data are provided by Karlsruhe Institute of Technology (KIT).
[3] Data are provided by German weather service (DWD).
[4] Data are provided by Landeshauptstadt Stuttgart.
[5] Ibid.

data are then processed using statistical procedures to determine the different city structures and building typologies. The city structure including urban geometry, land use, land cover, residential density, traffic etc. are used as TEB (Town Energy Balance) simulation settings, and the building typology information – including building use, geometry and age – are used as TRNSYS-simulation settings.

II. Urban climate simulation with TEB

The Town Energy Balance model TEB [5] [6] simulates the turbulent fluxes for urban areas using generic canyon geometry with detailed representation of the urban surface to resolve energy balances for walls, roads and roofs. The weather data with a spatial resolution of the 1 km for the LARSIM-model includes the effects of the topography and land use. They are further adjusted using the urban canyon model TEB, in order to integrate the small-scale climatic differences due to urban typologies, urban density, building use, and material properties.

III. Building energy simulation with TRNSYS

The complexity of the city structures and building types in Stuttgart are simplified based on generic indicators known to be decisive as far as thermal processes are concerned. These indicators are then combined in a matrix based on a 3-steps DOE design of experiments to build an extensive parameter study. The outcomes of the simulation are the energy demand for heating, cooling, lighting and ventilation.

IV. Statistical analysis of the outcomes

The outcomes from the building simulation are statistically analyzed using DOE-method. DOE-method is a statistical method for evaluating all influential variables on a process with as few as possible experiments. The main effects and the double interactions of all investigated indicators are thereby systematically analyzed, and mathematical models for linear regression are defined for determining the building energy demand of each individual building block.

V. Graphical representation of the outcomes

The spatial distribution of building energy demand for heating, cooling and lighting of the whole city of Stuttgart is then illustrated using GIS-techniques.

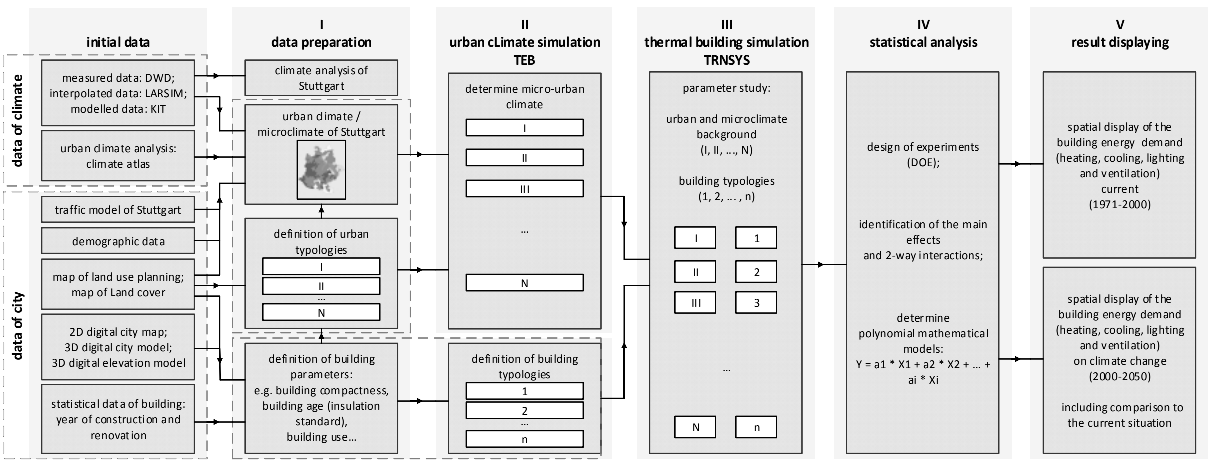

Figure 1: Methodology of this study.

3. Strength of UHI effect in Stuttgart

Long-term weather data from 13 DWD stations (German weather service) in or near to Stuttgart were initially considered for the period of 1983-2013. By considering only complete data sets of required meteorological key metrics, only the 3 stations Schnarrenberg, Neckartal and Echterdingen could be used (Figure 2A) which is not enough for the spatial interpolation of weather data for the whole city area. As a consequence, the KIT-weather data with the spatial resolution of 7 *km* were integrated (Figure 2A). Finally, the interpolated long term weather data with the spatial resolution of 1 *km* and hourly time resolution were given by the LARSIM model (Figure 2B). These data are based on measured weather data from weather stations disseminated in the whole land of Baden-Württemberg. Depending on the meteorological parameter, from 15 to 285 weather stations were used as references for the interpolation.

Figure 2B shows as an example the mean air temperature from 2003 to 2012. The mean air temperature difference between the highest and the lowest location is up to 2.4 *K*. The highest air temperature appears in the inner city and the industrial area, accentuated by their location in a valley.

Based on the 3 DWD weather stations, the temporal profiles of the UHI effect were also examined. The location of Schnarrenberg in the north of Stuttgart is characterized by low density districts in form of residential and commercial use, whereas the Neckartal shows the highest degree of sealed surfaces but the buildings nearby are not very tall. Echterdingen is located in the south and its climate is mostly influenced by the low density of building area. The trends of difference between each two locations are shown in the Figure 3 with the percentile 10% to 90%. Both the monthly and daily trends show that the air temperature difference between the warm Neckartal and cool Echterdingen is the largest and could reach 3.3 *K* in the early morning. The air temperature difference between Neckartal and Echterdingen and also between Schnarrenberg and Echterdingen are lower in the daytime than in the night, but the trend is reversed between Neckartal and Schnarrenberg. The urban structure of Neckartal with low and dense buildings is heated more easily than Schnarrenberg, and also cools down faster.

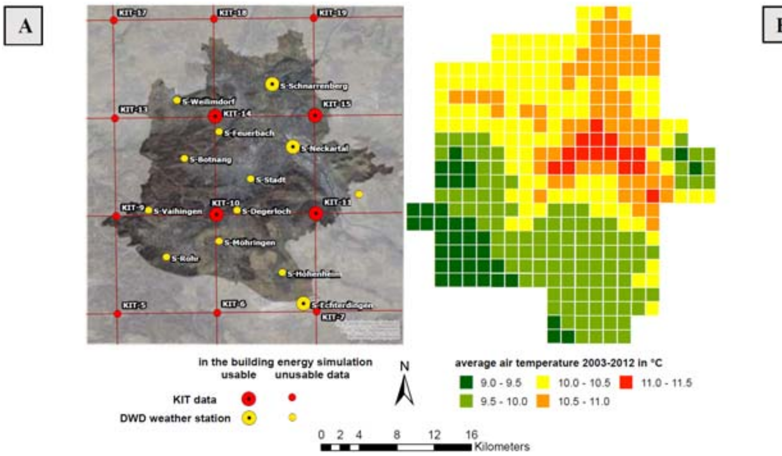

Figure 2: Locations of DWD weather stations / KIT points on the satellite map (A), average air temperature in Stuttgart with 1 km resolution (B). *Data source*: DWD, KIT, City of Stuttgart (A) and LUBW (B), own illustration.

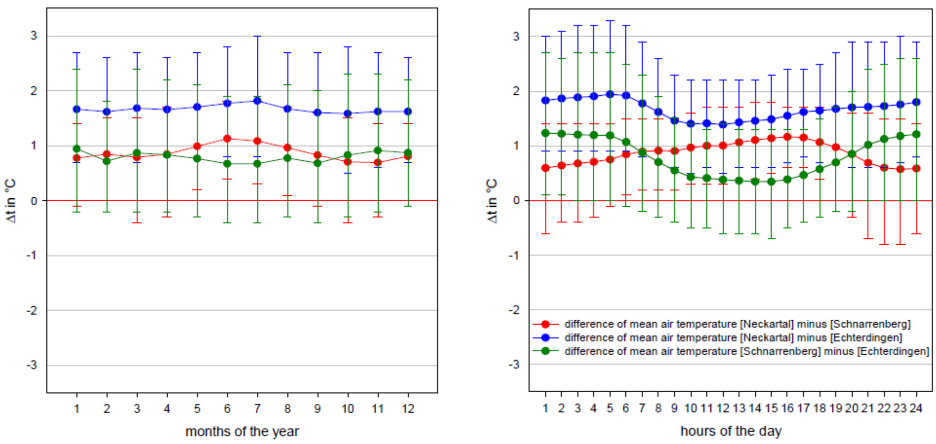

Figure 3: Air temperature difference from DWD weather station in average for the period 2003 - 2012.

4. Urban structure and building typology in Stuttgart

4.1. Consideration of urban structure and building typology for building energy simulation

The building simulations are undertaken at building level (Figure 4), but the results are presented at city block level, because the city block level offers the best detail information after the building scale which cannot be published for data privacy protection. The building energy simulation in this project uses generic indicators of urban and building instead of context-specific description of real buildings; the values range of each indicator is defined based on the real city blocks and buildings in Stuttgart. These indicators also depend on acquirable data for the city area of Stuttgart, and the spatial resolution of the data should also be high enough. The preliminary list of the indicators considered is given in Table 1. The data sources and some of the city and building indicators are listed and shown as maps in Figure 5 (In Figure 5, the map number 4-12 are cuts from the whole city in order to show more details).

Since urban structure influences the micro-climate, data of urban facets are used as TEB-simulation settings in order to convert the starting weather data (with the resolution of 1 km) into small-scale urban canyon weather data. Moreover, the building typologies influence also the energy demand, and they are included in the TRNSYS-simulation as settings. Additionally the influence of aspect ratio, which is already considered in the TEB-simulation, is also considered as the geometric relationship between buildings, and is also taken into account in the TRNSYS-simulation.

Based on 3D digital city maps (digital building model and digital elevation model), the building volume and surface area are calculated using ArcGIS-Tools separately (Figure 6 and Figure 7).

Table 1: Urban and building parameter used in the building energy simulation

indicator	**source**	**used in**		**Available spatial resolution**
		TEB	**TRNSYS**	
aspect ratio (H/W ratio)	3D digital city map	✓	✓	city block
residential density	statistical data	✓		city block
traffic	traffic model of Stuttgart	✓		50 m grid
building use	2D digital city map		✓	building
energetic condition of building	building age and time of renovation from 2D digital city map		✓	building
compactness of building	3D digital city map		✓	building
window ratio	building use and building age from 2D digital city map		✓	building
heated volume in the building	base area and number of floors		✓	building
orientation of window and building	none		✓	-
street orientation	none		✓	-

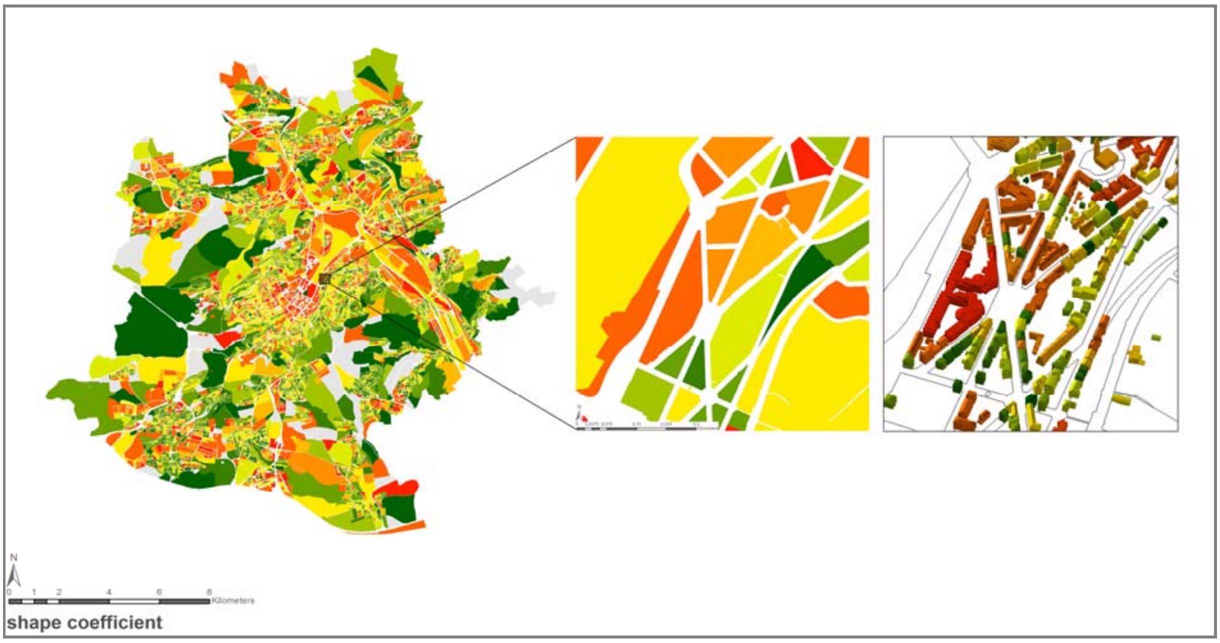

Figure 4: Calculation of shape coefficient: dynamic simulations with TRNSYS are undertaken at building level but the results are shown at city block level

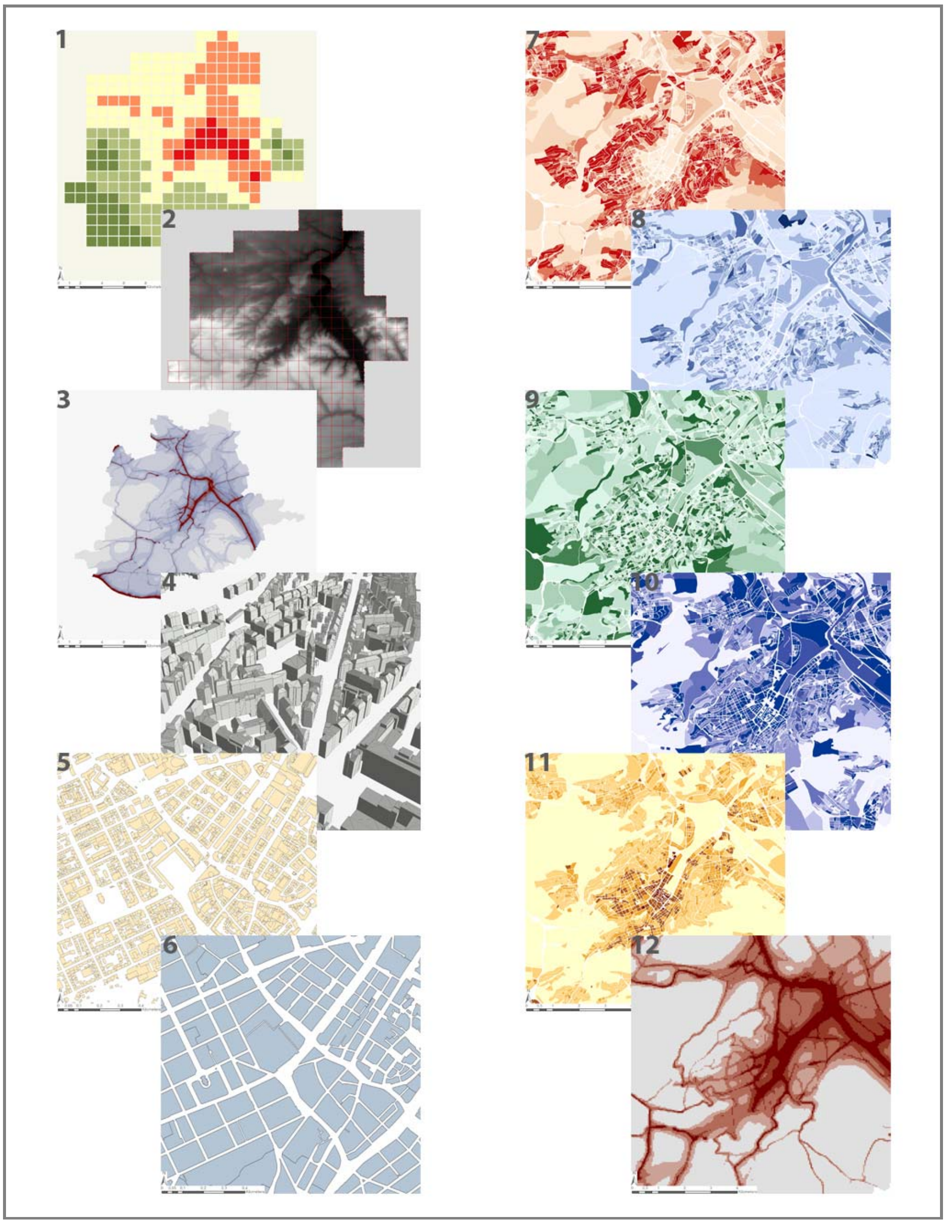

Figure 5: Data sources and parameters calculated.

Figure 5 shows on the left (1 to 6) the source data and on the right (7 to 12) the maps illustrating the indcators used to describe the city structure and buildings as used in TEB and TRNSYS simulations. The maps as numbered show the following:

1. weather data with 1km² resolution, as background site climate including the local effects like relief and vegetation. These are inputs for TEB and in adjusted form for TRNSYS.
2. Elevation model, showing the dependence of the climate background from geography.
3. NO_2 immission, is a map of the anthropogenic heat used in TEB simulations.
4. Digital 3D building model
5. digital 2D city map with information on building use, age, size etc.
6. city block map, which is a simplified representation used later for results mapping.
7. building use: eg. residential versus non-residential building
8. building age: map specifying the building typologies according to their built date (here example between 1958-1968), relevant inter alia for insulation standard determination.
9. building volume
10. shape coefficient is a map summarizing the main geometric property of the buildings in relation with heat conservation or losses (replaces Area Volume ratio)
11. aspect ratio: describes the city density in form of building heigt to street width, decisive for shading issues
12. anthropogenic heat release (traffic)

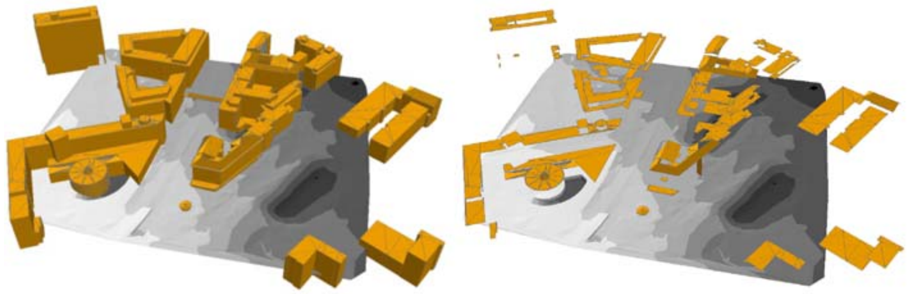

Figure 6: Calculation of building volume (left: original 3D building model and digital elevation model; right: roof of the 3D building model). Data source: Landeshauptstadt Stuttgart 2013, own processing.

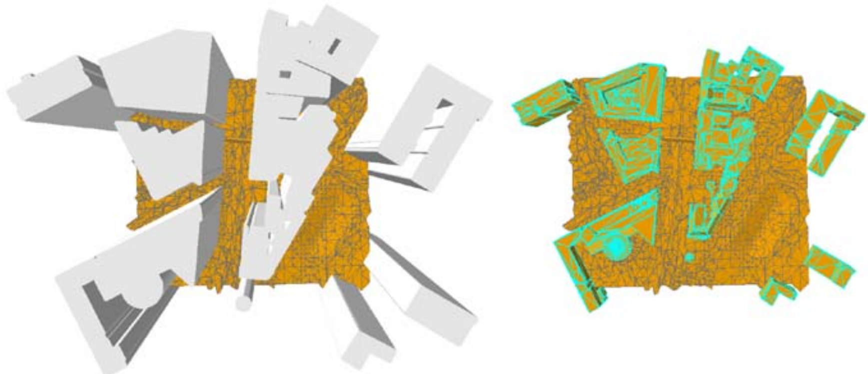

Figure 7: Calculation of building surface area (left: 3D building model, digital elevation model and extruded building roofs; right: polygons of building surface with highlight). Data source: Landeshauptstadt Stuttgart 2013, own processing.

4.2. Parameterization of urban and building typology and simulation steps

Building models are built with parameters in equidistant-steps. For buildings, the compactness indicator A/V ratio has dependency on the size of building, it is impossible to get for each step of volume the same steps of A/V ratio (see Figure 8). Another indicator of compactness: shape coefficient is defined (1). The shape coefficient describes the degree of deformation of a building in comparison to a sphere with the same volume. The simulation steps of volume 216 m^3, 4738.5 m^3, 9261 m^3 and the steps of shape coefficient 1.07, 1.15 and 1.23 are used. These combinations contain the A/V ratio from 0.29 to 1.38. Considering thermal transfer between inside and outside the building, 5.5 sides (the total area of roof and facades plus the half area of ground) are used for calculating building envelop area.

$$shape\ coefficient = \frac{\sqrt[6]{(4\pi)^5}\sqrt{a}}{\sqrt[3]{3v}} \qquad (1)$$

a is building surface area considering 5.5 sides of building envelope,
v is building volume.

Considering the difference of thermal characteristic of window and building envelop, window ratio is defined as the ratio of window area to 5.5 sides building envelope area. 20%, 40% and 60% are set as the simulation steps.

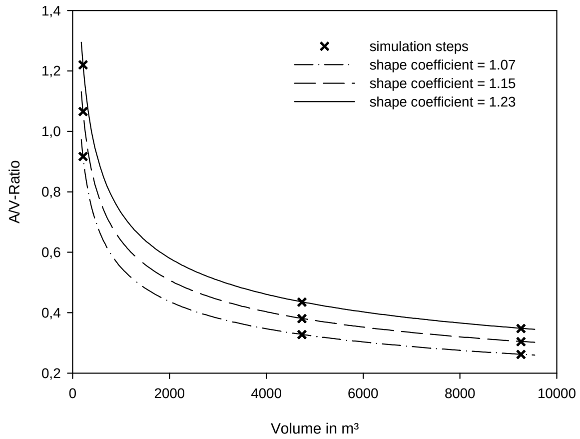

Figure 8: Simulation steps of compactness and building volume.

5. Test run of building energy simulation with consideration of urban climate

In order to illustrate the simulation procedure in this project as described under chapter 2 (parametric study using TRNSYS + statistical analysis), an example of a simulation is presented based on a previous research (see e.g. [1] and [2]). Five different urban and building indicators are examined by assigning 3 stages of values to each indicator (Table 2): A) aspect ratio, B) solar orientation, C) window ratio, D) thermal insulation and E) thermal construction of building.

Table 2: Variables of the parametric study used for TEB and TRNSYS simulations

	coded form →		-1	0	1
urban context	A =	aspect ratio	H/W = 0.2	H/W = 1.0	H/W = 0.8
	B =	solar orientation	NWSE (-60° from S)	NS (180°, 0°)	NESW (+60° from S)
building	C =	window ratio	30% Perforated facade	60% row facade	90% glass facade
	D =	thermal insulation	$U_{wall} = 0.65$ $U_{glass} = 2.1$	$U_{wall} = 0.4$ $U_{glass} = 1.4$	$U_{wall} = 0.15$ $U_{glass} = 0.7$
	E =	thermal construction	light-weighted construction	-	massive construction

Source: Ali-Toudert 2012 [7].

Building energy simulations were run for 162 cases consisting of all possible combinations of the 5 indicators A to E. All of the 162 combinations were tested with 2 climate datasets: the standard climate data TRY 12 (test reference year for the region 12, in which Stuttgart is located, data source: DWD [8]) and by urban climate influenced situation (TRY 12 + urban climate, data source: DWD [8]). So, a total of 324 simulations have been run for the test, whose outcomes are analyzed with the statistical method design of experiments.

The main results from the simulations are summarized in Table 3and Figure 9. The decrease in the energy demand for heating depends on the urban heat island, up to a maximum case of -8.68 *kWh/m²yr*. The poorly insulated building with high window ratio shows the greatest decline, since in this case the influence of the climate boundary conditions is the greatest because of more heat transport. For the same reason, the well-insulated building with small windows shows the minimum decrease of -0.32 *kWh/m²yr*. Conversely, the energy demand for cooling becomes higher in consideration of the urban climate (Table 3). The smallest increase is +1.86 *kWh/m²yr* and can reach up to +5.76 *kWh/m²yr*. The global energy demand (for heating and cooling) shows an increasing trend (Table 3) up to +6.69 *kWh/m²yr* by considering the urban climate. In a few cases, when the energy demand for heating is especially lower in a context including urban climate effects than the standard climate dataset, the sum of energy demand for heating and cooling can also be lower than the standard case up to a minimum of -2.05 *kWh/(m²yr)*. If the energy demand for heating, cooling, lighting and ventilation is added up, the urban climate shows a negative influence. The only exception is the poor insulated building with high window ratio, and in this case the energy demand goes down (Figure 9).

Table 3: Energy demand for heating and cooling for an office building in consideration of standard TRY 12 and urban climate adapted TRY 12.

energy demand for office building	standard TRY 12			TRY 12 + urban climate		
	min.	max.	band-width	min.	max.	band-width
heating	1.9	52.6	50.6	1.5	45.4	43.9
cooling	4.9	20.9	16.0	7.1	23.3	16.2
heating and cooling	8.4	69.0	60.5	11.5	67.1	55.6

Source: Ali-Toudert 2012.

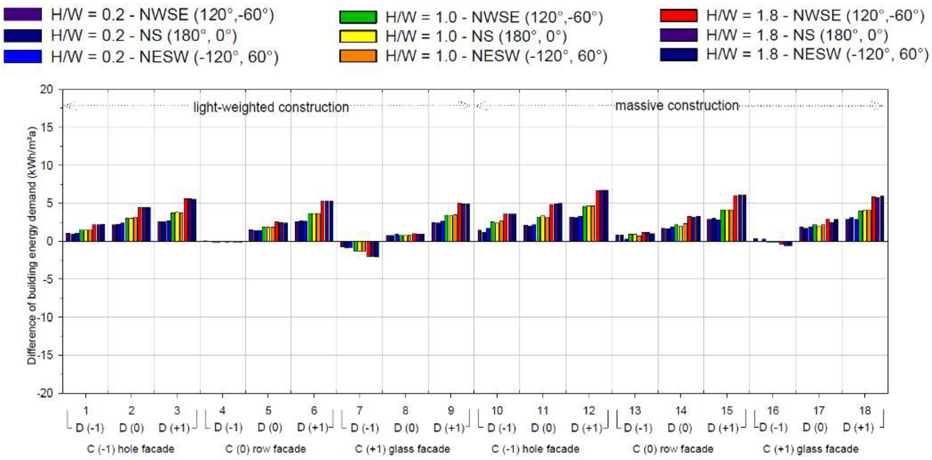

Figure 9: Difference of energy demand for heating, cooling, lighting and ventilation between the building in urban climate and in standard climate of TRY 12. Source: Ali-Toudert 2012 [7].

Table 4 shows the statistical analysis of the outcomes of all the 324 simulations exemplarily. The analysis is undertaken to test the weight of the influence of indicators and also the weight of the combinations on the sum of heating and cooling energy demand when urban climate is taken into account (Table 4 left) and to test the influence on the difference of energy demand between the urban climate case and the standard climate situation (Table 4 right). The main effects of all the studied variables and their double interactions are quantified based on 11 different mathematical models. The adjusted R² shows the hit rate of the models.

If looking at Table 4, it's clear how about the 45.9% of the energy demand for heating and cooling is caused by thermal insulation (parameter D: thermal insulation) (Table 4 left). The parameter C (window ratio), E (thermal construction) and their interaction CD raise the hit rate to R^2 = 98.7% with the model No. 4. The extensions of model 4 bring only marginal improvement, thus the model 4 can be declared as sufficiently representative. The coefficients show if and how much positive or negative influence the parameters have. For example, the improvement of thermal insulation (D), the reduction of window ratio (C) and massive construction (E = 1) reduce the energy demand.

Table 4 right shows the main influence of each parameter and their double interactions on the difference of energy demand compared to the standard climate situation. The parameter A (aspect ratio) becomes more important and the air temperature becomes higher when the aspect ratio (H/W ratio) is higher.

Table 4: Statistical analysis of building energy simulation outcomes for heating and cooling with consideration of urban climate (left) and the difference of energy demand between urban climate case and standard climate case TRY 12 (right).

urban climate

Model Summary

Model	R	R Square	Adjusted R Square	R Square Change
1	,680[a]	.462	.459	.462
2	,833[b]	.695	.691	.233
3	,935[c]	.875	.873	.181
4	,994[d]	.988	.987	.113
5	,997[e]	.994	.993	.006
6	,998[f]	.995	.995	.002
7	,998[g]	.996	.996	.001
8	,998[h]	.997	.997	.001
9	,999[i]	.997	.997	.000
10	,999[j]	.998	.997	.000
11	,999[k]	.998	.997	.000

Coefficients*

Model	B		Sig.
11	(Constant)	27.508	.000
	D	-11.630	.000
	C	8.251	.000
	E	-5.936	.000
	CE	-7.035	.000
	Dq	2.272	.000
	Cq	1.241	.000
	Bq	.810	.000
	AC	-.544	.000
	AE	.336	.000
	AD	.372	.000
	A	.162	.019

delta [urban climate - standard climate]

Model Summary

Model	R	R Square	Adjusted R Square	R Square Change
1	,796[a]	.634	.632	.634
2	,870[b]	.756	.753	.123
3	,914[c]	.836	.832	.079
4	,946[d]	.894	.891	.059
5	,969[e]	.939	.937	.044
6	,980[f]	.960	.959	.022
7	,986[g]	.973	.972	.013
8	,990[h]	.980	.979	.007
9	,991[i]	.982	.981	.002
10	,992[j]	.983	.982	.001
11	,992[k]	.984	.983	.001

Coefficients*

Model	B		Sig.
11	(Constant)	.813	.000
	D	1.893	.000
	C	-.833	.000
	E	.546	.000
	AD	.705	.000
	CE	.614	.000
	AC	-.429	.000
	A	.269	.000
	AE	.200	.000
	Cq	.170	.000
	CD	.088	.000
	Bq	.096	.027

1	a. Predictors: (Constant), D
2	b. Predictors: (Constant), D, C
3	c. Predictors: (Constant), D, C, E
4	d. Predictors: (Constant), D, C, E, CE
5	e. Predictors: (Constant), D, C, E, CE, Dq
6	f. Predictors: (Constant), D, C, E, CE, Dq, Cq
7	g. Predictors: (Constant), D, C, E, CE, Dq, Cq, Bq
8	h. Predictors: (Constant), D, C, E, CE, Dq, Cq, Bq, AC
9	i. Predictors: (Constant), D, C, E, CE, Dq, Cq, Bq, AC, AE
10	j. Predictors: (Constant), D, C, E, CE, Dq, Cq, Bq, AC, AE, AD
11	k. Predictors: (Constant), D, C, E, CE, Dq, Cq, Bq, AC, AE, AD, A

* Dependent Variable: SQSENS_AB

1	a. Predictors: (Constant), D
2	b. Predictors: (Constant), D, C
3	c. Predictors: (Constant), D, C, E
4	d. Predictors: (Constant), D, C, E, AD
5	e. Predictors: (Constant), D, C, E, AD, CE
6	f. Predictors: (Constant), D, C, E, AD, CE, AC
7	g. Predictors: (Constant), D, C, E, AD, CE, AC, A
8	h. Predictors: (Constant), D, C, E, AD, CE, AC, A, AE
9	i. Predictors: (Constant), D, C, E, AD, CE, AC, A, AE, Cq
10	j. Predictors: (Constant), D, C, E, AD, CE, AC, A, AE, Cq, CD
11	k. Predictors: (Constant), D, C, E, AD, CE, AC, A, AE, Cq, CD, Bq

a. Dependent Variable: SQSENS_AB

Source: Ali-Toudert 2012 [7].

6. Conclusions

In this study, the building energy demand is calculated using numerical modelling. The influences of urban climate resulting from urban structure and building typology are considered in the simulation.

The strength of UHI effect of Stuttgart is thus analyzed and the highest difference of the mean air temperature between the two weather stations Neckartal and Echterdingen is 3.3 K in the morning.

Generic indicators of the urban structure and building typologies are used and the influence of each indicator is determined systematically with a statistical method. In an example showing the investigation procedure adopted in this project, five different building and urban indicators with two climate boundary conditions were investigated. In general, the building energy demand for heating tends to be lower if urban climate effects are included compared to a standard climate situation, while energy demand for cooling tends to be higher. The building energy demand for both heating and cooling, as well as for heating, cooling, lighting and ventilation tends to be higher, yet with some exceptions. This example shows that urban climate must be studied in consideration of specific boundary conditions, since they affect the building energy demand.

In this project numerical simulations will be conducted following the example above after the determination of the appropriate morphological and typological indicators for Stuttgart. The DoE statistical post-processing will enable the mapping of the resulting energy demands.

7. Further steps

The project is ongoing. The building energy simulations with the building and urban parameters of Stuttgart under the consideration of the local urban micro-climate are currently in processing. The systematic parameter study will also be carried out. A map with the spatial distribution of energy demand in Stuttgart will be drawn with GIS-method.

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