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Building Energy Demand under Urban Climate and Climate Change conditions with consideration of Urban Morphology and Building Typology - GIS Mapping of the City of Stuttgart

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1. Introduction

This paper reports on preliminary results of the ongoing KLISGEE project which addresses the issue of quantifying the consequences of the urban climate and mid-term climate change on the energy demand of buildings for the case of Stuttgart, Germany. The method applied combines 1) numerical modelling using TEB and TRNSYS, 2) statistical analysis for pre- and post-processing of the data and 3) GIS-methods.

The KLISGEE project is being carried out in the framework of the Program KLIMOPASS-Teil 1 funded by the land Baden-Württemberg, Germany.

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 (Bremicker et. al. 2013), ii) weather data sets generated from atmosphere modelling for a 30 years period (1971-2000) and iii) measured weather data from 3 weather stations . 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 ; ii) statistical data of residential density ; iii) traffic data of Stuttgart. The 2D and 3D digital city 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 (Masson 2000, Masson et. al. 2002) 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.

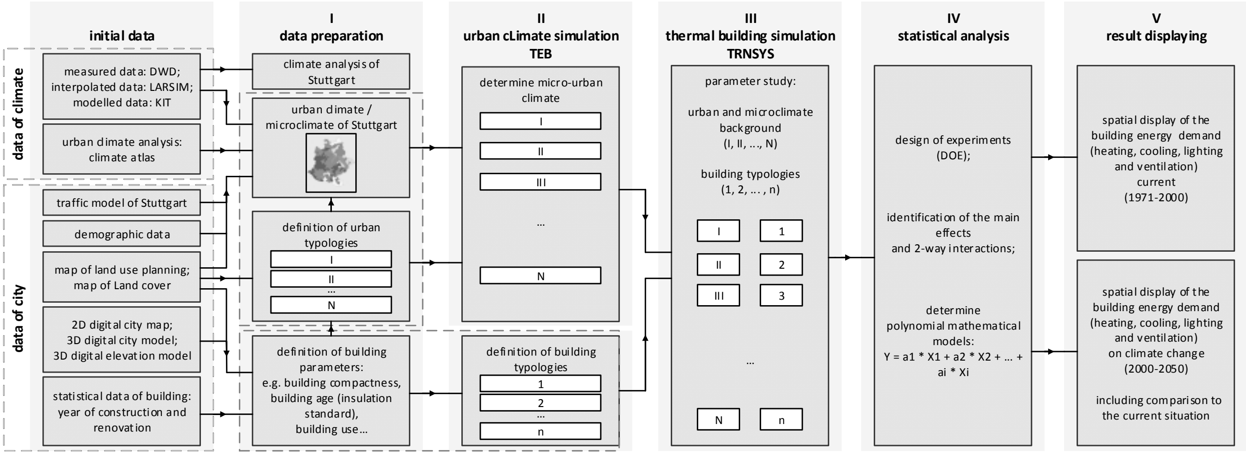

Figure 1: Methodology of this study.

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. Based on the 3 DWD weather stations, the temporal profiles of the UHI effect were also examined.

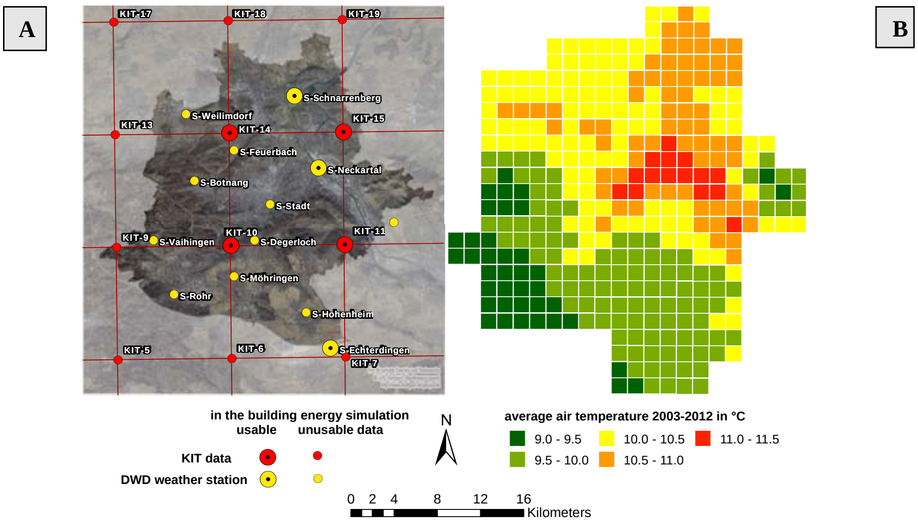

Figure 2: Locations of DWD weather stations / KIT points on the satellite map (A), average air temperature in Stuttgart with 1 km resolution (B). Data source: DWD, KIT, City of Stuttgart (A) and LUBW (B), own illustration.

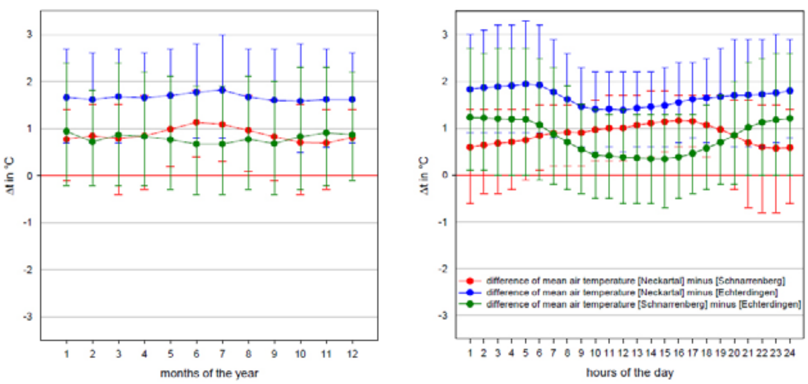

Figure 3: Air temperature difference from DWD weather station in average for the period 2003 - 2012.

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		✓	-

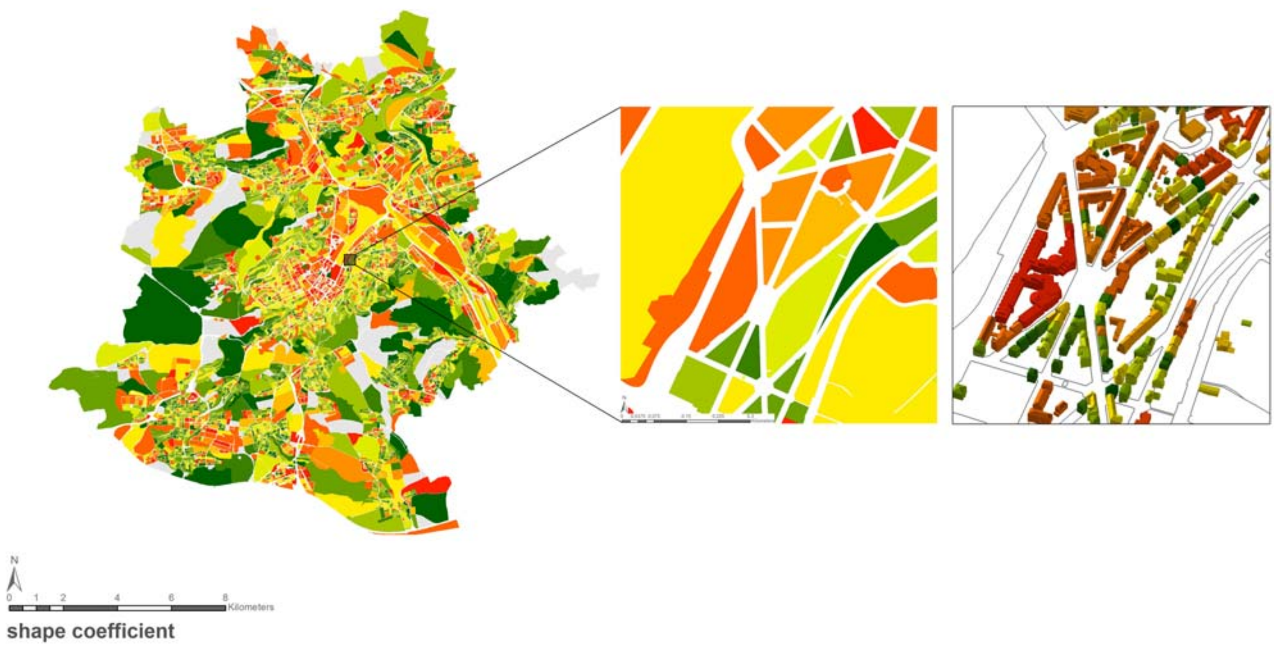

Figure 4: Calculation of shape coefficient: dynamic simulations with TRNSYS are undertaken at building level but the results are shown at city block level

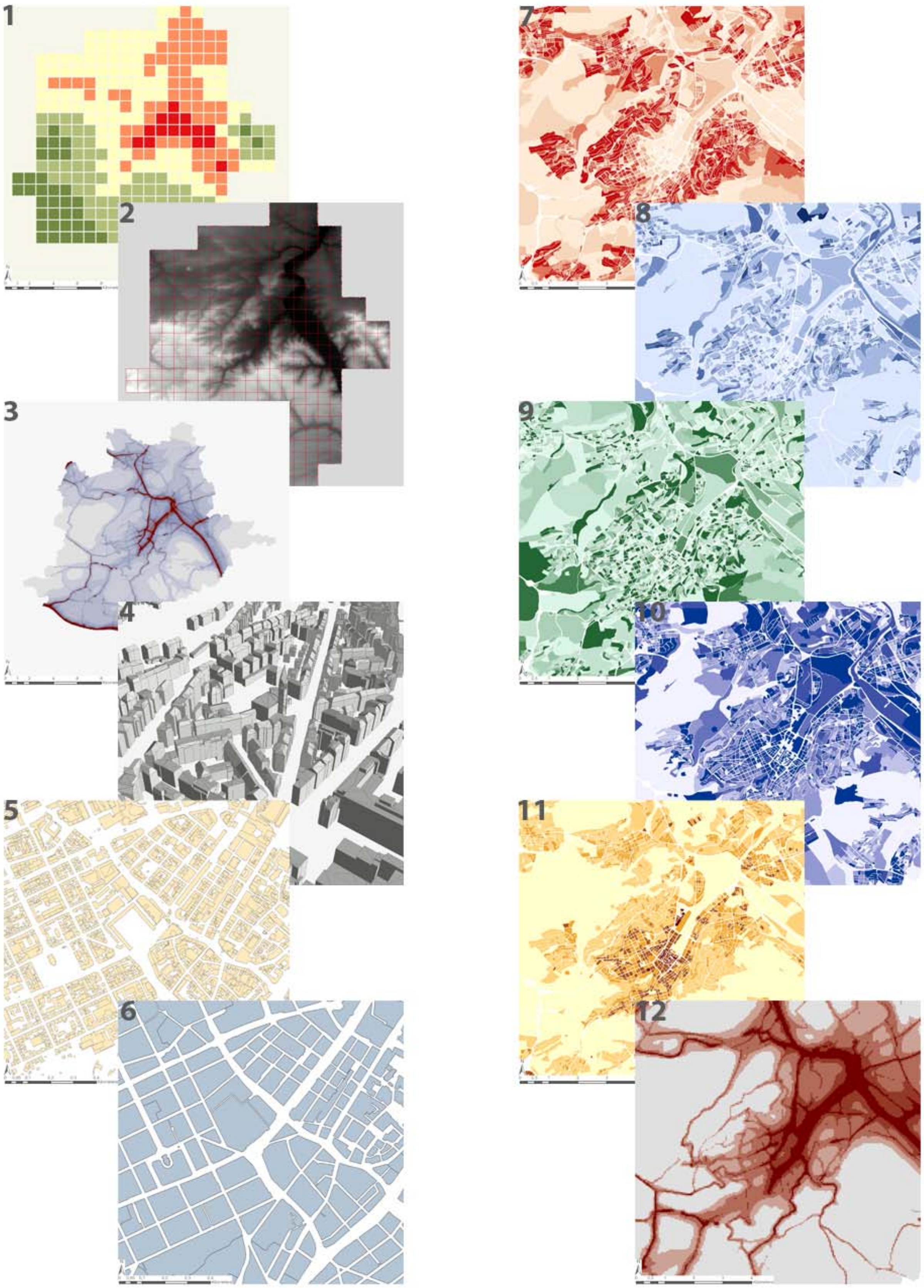

Figure 5: Data sources and parameters calculated.

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. NO2 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)

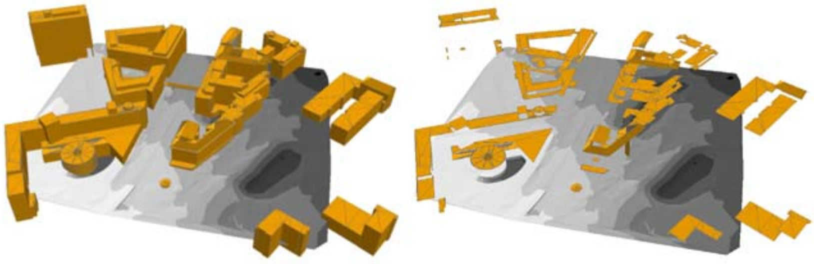

Figure 6: Calculation of building volume (left: original 3D building model and digital elevation model; right: roof of the 3D building model). Data source: Landeshauptstadt Stuttgart 2013, own processing.

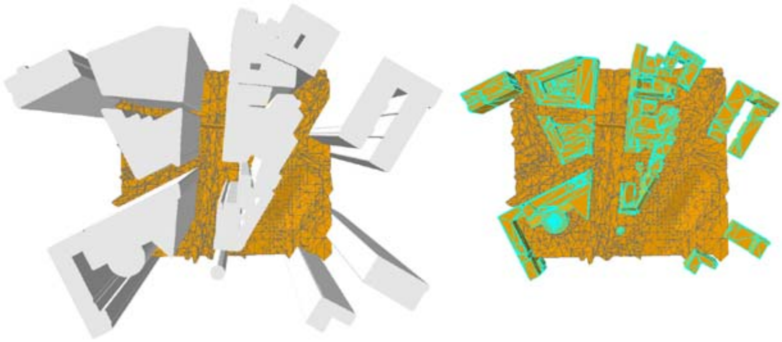

Figure 7: Calculation of building surface area (left: 3D building model, digital elevation model and extruded building roofs; right: polygons of building surface with highlight). Data source: Landeshauptstadt Stuttgart 2013, own processing.

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 m³, 4738.5 m³, 9261 m³ 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.

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

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.

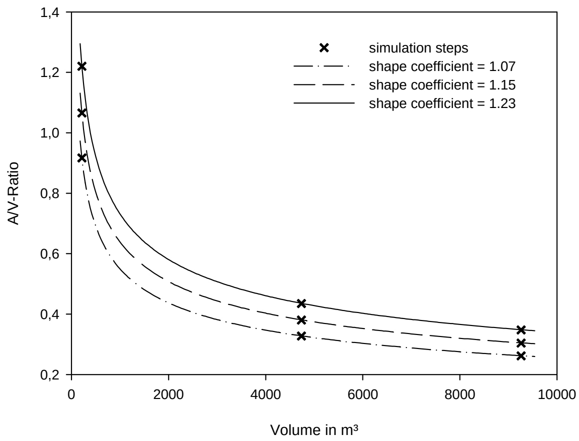

Figure 8: Simulation steps of compactness and building volume.

5. Building energy simulation with consideration of urban climate

Via parametric study in some previous research, some results about the influence of building parameter on the energy demand have been offered (see Ali-Toudert 2011 and 2013, Ali-Toudert and Ji 2014). These Parameters will be adapted in this study especially for city Stuttgart. 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.

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.

In order to make the simulation, which is carried out on building scale, for the whole city Stuttgart possible, buildings in Stuttgart are parameterized.

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.

Acknowledgment

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