

3D City Modelling for Urban Scale Heating Energy Demand Forecasting

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ABSTRACT

The purpose of this project is the development of an urban energy management tool to predict the heating energy demand of urban quarters and analyse strategies to improve the building standards. A forecast of the heating energy demand of each building can be used to determine the potential for heating energy reduction at a city quarter scale. To achieve this goal, a special method is used, which enables an automatic extraction of the building's heating volume from a geo-information system. The buildings' volume, which consists of the building footprints and the measured building heights (from airborne laser scanning) enables the generation of a 3D city model of the analyzed area. Based on this 3D city model an input file, which can be read by the Building Simulation Model, is generated. Special focus is put on a method for modeling the heating energy demand of the buildings with the least input parameters possible, but giving reliable forecast results. A simple transmission heat loss method and an energy balance method were tested. In both cases, there was a good correlation between the measured and calculated annual values for the most buildings of the demonstration site Scharnhäuser Park near Stuttgart/Germany. The good results also show that a 3D city model (even with low geometrical detail) can be used for energy demand forecasting on an urban scale.

KEYWORDS

3D city model, building simulation, heating energy demand forecasting

INTRODUCTION

The research work presented in this paper is part of the European Union research project POLYCITY. The test area is the residential area Scharnhäuser Park, located near Stuttgart. The purpose of this research work is the development of an urban energy management tool to predict the heating energy demand of urban quarters and analyse strategies to improve the building standards. A forecast of the individual heating energy demand of each building can be used to determine the potential for heating energy reduction at a city quarter scale. The goal of this research project was to estimate such a potential for the whole area of Scharnhäuser Park.

In order to achieve this goal an urban model of the analyzed area will be necessary. Various urban models have been developed and are used in the urban domain, to perform, for example, building energy consumption analysis. Special focus is put on 3D GIS (3 Dimensional Geographic Information Systems), from which 3D city models are derived. [Metral, 2009] also described the need for semantically enriched 3D city models, which not only focus on the geometrical/visual aspect of the real world environment. Especially for simulations additional information is necessary in order to provide input parameters to the simulation (e.g. building type, heat transfer coefficients, etc.). A prototype application for flexible management of these 'semantically enriched' models that was used for the energy demand forecast scenario will be presented in this paper. The effect of urban geometry on energy consumption still remains understudied. The reason is the difficulty of modelling complex urban geometry [Ratti, 2009]. Therefore, this paper will describe how to use a very simple 3D urban model of Scharnhäuser Park to predict the heating energy forecast.

For the purposes of urban scale simulation, it is important to achieve a good compromise between modelling accuracy, computational overheads and data availability. These are the criteria applied in the selection of an appropriate modelling technology [Robinson, 2009]. Most building simulation models, which are available on the market, require a large amount of data input [Mavrogianni, 2009]. The level of detail of input parameters depends mostly on data availability, which could lead to a problem with data acquisition to model the heating energy demand at city scale. This results in a disbalance between a high demand for input parameters and data availability on urban scale. Therefore, the very important aspect of this work was to find a solution to forecast the heating energy demand of the buildings with the least input parameters possible, but giving reliable results. This also incorporates investigations on the detail of available models and how reliable simulation results are, which are based on these models.

Furthermore, as a consequence of the improved quality of thermal properties of buildings due to energy regulations, overall energy use associated with building characteristics is decreasing, making the role of the occupants more important [Santin, 2009]. Therefore, there is still a lack of studies regarding the impact of consumer behaviour.

In the presented approach a Geographic Information System (GIS) together with an Access database were used in order to facilitate the acquisition of building specific data, like outer building surface. Then, a method was used, which enabled an automatic extraction of the building's heating volume via a geo-information system. Using the building volumes, which consist of the buildings' footprints and the measured buildings' height (from airborne laser scanning), it is possible to generate a 3D city model of the analyzed area. The 3D city model is then managed by a 3D data management framework. This framework is capable of reading different geospatial data formats and databases into an internal data representation. Having transformed the buildings into the internal representation, the framework could be used to analyse the 3D data; in the presented case it was possible to identify outer walls and walls between buildings.

A rather simple programme used several components of the framework to analyse the building model and to write an output file, which could be read by the Building Simulation Model.

Two versions of calculation models were tested with regard to forecast the heating energy demand of the buildings. One of them considered only the transmission losses through the outer building envelope and another one considered the whole energy balance of the building.

Both models were used to predict the heating energy demand of the whole residential sector of Scharnhäuser Park. The additional publication of the results via Web Application should make residents aware of the sustainable urban development in their city.

Case study area

Scharnhäuser Park (SHP) is a residential area, which is located at the southern border of Stuttgart, Germany. This area is a former military area where working places, residential areas and green park sections are integrated to result in a harmonious living and transportation environment with high comfort and low energy consumption. The area of Scharnhäuser Park is 150 hectares and 7000 inhabitants live there.

About 80% of the energy demand of the whole area of SHP should be supplied from renewable energies. The main heating and electrical energy is delivered to the buildings of SHP from the 6.3 MW_{th} wood fired co-generation plant.

Data acquisition

Geometries via GIS

The program GeoMedia Professional made it possible to extract from the geo-information system the following information:

- the building footprint area and building type from ALK-map
- average building height from laser scanner data



Figure 1. GIS map with building footprints and aero photo Source: Google Earth]

Measured heating energy consumption data

The annual heating energy consumption data of all buildings of Scharnhäuser Park originate from the archive of the municipal utility company Esslingen am Neckar GmbH. These data was delivered in form of Excel or paper sheets. In order to organize these data, a data model was developed and implemented in an Access database.

Physical building data

The only physical data needed for the simulation model are the heat transfer coefficients (U-values). Scharnhäuser Park is a modern residential area with low energy buildings. As the buildings were all constructed within a short time period, where the same legal requirements applied for thermal standards, the physical values needed for the simulation model are almost equal for all buildings. Therefore these values have been taken from the thermal insulation specifications available as average values for two building groups (row houses and multi-family houses).

Weather data

Air temperature and global radiation data was provided for the whole year 2008 and 2009 from the weather station placed in the analyzed residential area Scharnhäuser Park.

METHODS**GIS-interface providing input for simulation model**

The given building footprints together with the measured building height are used to generate a topologically consistent 3D city model [Ledoux and Meijers 2009]. This topologically correct model created according to the approach of [Ledoux and Meijers 2009] is not an extrusion of each individual footprint by the given height; it also takes into account buildings that share walls. The resulting dataset of the topologically correct model included a geometrical dataset of the model encoded in CityGML (OGC, 2008) and a text file with the information which wall is an outer/inner wall, as well as identifiers for roof and floor faces.

In order to use a more detailed model compared to the extruded block model we are working on the analysis, the semantic enhancement and preparation of a 3D city model with a higher level of detail provided by the city of Stuttgart. This model would then have e.g. detailed roof geometry and would not only be based on extruded footprints. A classification separating geometry into roof, floor and wall faces is already supported. A very important task is also the validation of the geometry, the topology of the existing 3D city model as well as the correct classification of geometry.

The influence of the higher degree of detail on the simulation results and their reliability needs to be investigated in the future.

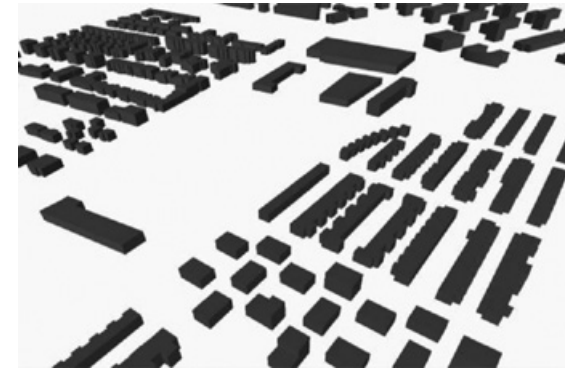


Figure 2. Topologically consistent 3D block model of Scharnhäuser Park

These approaches support [Metral, 2009] demanding a semantically enriched model in order to support applications like energy demand calculations. In the presented approach it is essential for calculations to know which faces are inner/outer walls, roofs and floors. This kind of classification can only be done if the model is generated according to specific semantics or a specific ontology. Additional information like year of construction, building type, etc. can also be useful for the presented approach and can be integrated into the model as part of future work.

Based on this topologically correct 3D city model (block or detailed), the total area of outer walls, walls between buildings, ground floor and roof can be calculated per building as shown in Table 1 for the above example.

Table 1. Example of data calculation

Building ID	Ground Floor Area m ²	Internal Wall Area m ²	Outer Wall Area m ²	Roof Area m ²
ID1	34	60	200	34
ID2	45	150	270	45
ID3	24	90	210	24

In order to calculate the required values an integration of several data streams was necessary. A 3D data management framework developed at HfT Stuttgart was used in order to access the different information sources, calculate the required values and write them to a file readable by the simulation tool. The framework architecture is highly modular and applications can use specific components that are suitable for the

task to be solved. The framework provides modules for 3 major areas: data input (connectors), data manipulation (data mapping) and data output (creators) (see Figure 3).

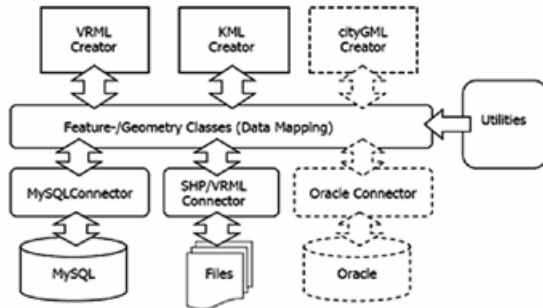


Figure 3. The 3D data management framework

The interface that generates the output for the simulation tool is developed on top of this framework using several components in order to produce the appropriate output for the simulation model. The framework is used to connect to the ESRI shape-file that included the original building footprints and heights of the buildings (used for extrusion) and to connect to the CityGML file holding the semantic 3D city model. The data mapping components are used to analyze the 3D city model geometry, connect the wall classification information and to calculate the overall inner/outer wall area per building. The interface component writes this information into a CSV text file that can be read by the simulation model, providing functionality to adjust the output format to possible requirements of specific simulation tools.

The window area in this case was calculated as a part of the outer wall area: 12% by row houses and 20% by multi-family houses. The so prepared geometry data for each building was put in one data file and serves as a GIS-interface for the simulation model.

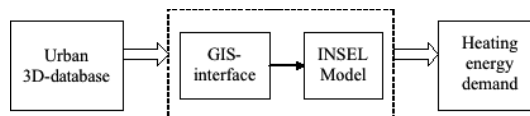


Figure 4. The workflow of data exchange

Calculation and simulation model

The *GIS-interface-file*, which includes building geometries, was finally fed into the Building Simulation Model by using the software INSEL (www.insel.eu). In order to achieve reliable results regarding the heating energy demand with less input as

possible, two versions of models have been tested. The first one (Model 1) calculated the heating energy demand by taking into consideration only the transmission losses through the outer envelope of the building. The second model (Model 2) considers the whole energy balance with transmission and ventilation losses as well as solar and internal gains following the calculation procedure from European standard DIN V 18599 [DIN V 18599].

In both models some assumptions have been made; in Model 1 the heating set-point temperature was set to a constant value of 20°C and in the Model 2 following settings have been specified: set-point temperature of 20°C, air change rate of 0,5 1/h and internal heat gains of 5 W/m².

Both models were used to calculate the annual heating energy consumption for all residential buildings in Scharnhäuser Park. The results of heating energy demand were verified by the measured annual heating energy consumption values for all buildings.

RESULTS

Comparison between calculated and measured data

The residential sector of Scharnhäuser Park is divided into two building categories: the one- and two-family row houses and the multi-family houses. The following figure shows the comparison between the measured and calculated annual values for all multi-family houses.

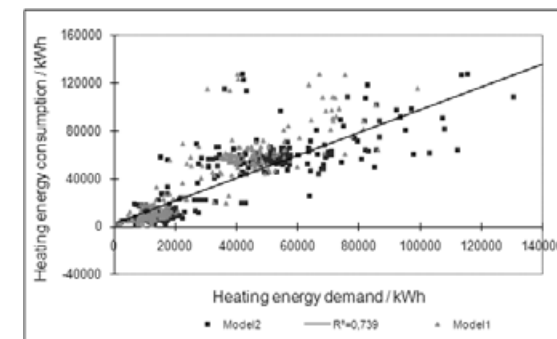


Figure 5. Comparison between annual calculated and measured values for multi-family houses

In the figure above we can see a quite good correlation between measured and calculated values in case of many buildings, but the analysis also indicates some extreme deviations, which lead to the quite high average deviations between measured and calculated values; 30% (Model 1) and 26% (Model 2). The same fact occurs by analyzing the one- and two-family row houses. Here the average deviation between measured and calculated values is of 28% by Model 1 and of 30% by Model 2. Therefore, it was

necessary to find out the reasons for these extreme deviations, which will be discussed in the next chapter.

The more general comparison between the measured and calculated values results in a better correlation, especially in case of Model 2. This comparison doesn't consider each of the buildings separately but as a whole residential sector, which is divided into row houses and multi-family houses.

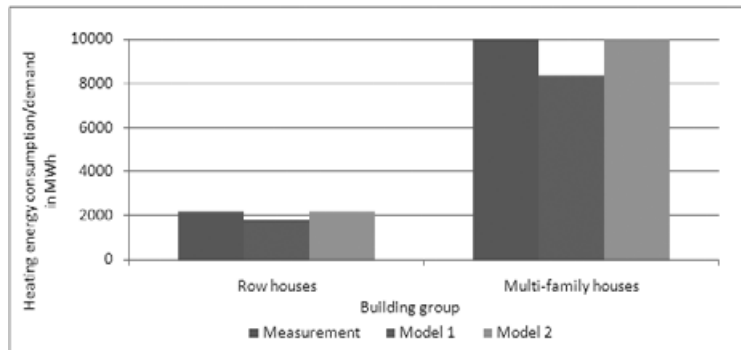


Figure 6. Total deviations between measured and calculated values

DISCUSSIONS

Explanation of the uncertainties

The reason for the discrepancies between measured and calculated values can be seen in the level of details of the 3D city model used. 80% of the buildings in SHP are of flat type; therefore in this case the block model (Level of Detail 1 – LOD1) seems to be enough for the extraction of the building heating volume. In case of buildings with detached roofs, LOD1 could not be enough for our purpose. Another reason is that for the buildings built after 2002 no laser scanner data are available and therefore the height value was put as min. of 7,5 m. These could lead to underestimate the building's heating volume. One more aspect, which could also be mentioned, is the fact, that in many cases the heating energy consumption value is a value not for one building but for a group of buildings (share energy meters). This fact can result in not accurate values by considering each of the buildings in this group separately. Also the approximation of the heating consumption for warm water, which was set as 12,5 kWh/m²a and subtracted from the total annual heating energy consumption values could lead to some discrepancies and therefore to the deviations between measured and calculated values. In the future also the user behavior related parameters, e.g. different operational schedules will be analyzed in details to reduce these uncertainties.

Comparison with other available methods

The heating energy demand of households in Germany at the residential district level can be estimated by using several methods. One of them is a simple method based on the typification of the districts, where the heating energy consumption is calculated with the characteristic parameters for the appropriate district type. The method presented here considers not only the city-scale, like it is done in these methods, but also the building scale. Here, the heating energy demand is calculated for each building separately and then summed up to the heating energy demand at city scale.

In the second one - a detailed laser scanning method- the heating energy consumption is based on three dimensional geometry data estimated from the Aerial survey of the buildings. Alternatively only 2 dimensional data from so called ALK maps can be used. [Blesl, 2010] uses a method, which is based on the laser scanner data and the thermal images to estimate the data needed for the calculation of the heating energy demand. The method described in this paper is very similar to the method of [Blesl, 2010], but uses physical parameters, which are taken from the building specification certificates for some representative buildings of the whole residential sector of Scharnhäuser Park. Most methods that have been developed uses building simulation models, which need many detailed input values [Mavrogianni, 2009]. Other methods, like the [Jones et. al., 1999] model are very general and calculate the heating energy demand by using very general characteristic parameters. The here presented method for the heating energy forecasting at city scale shows the possibility to calculate the heating energy demand by using calculation models with different levels of details. It was proved that even very simple model, which considers only the transmission losses through the outer building envelope, is suitable for predicting the heating energy consumption on a city-scale. The more complicated model, which considers the whole energy balance of the building, gives additionally a possibility to validate the user related parameters, like set-point temperature, internal heat gains, and air exchange rate.

There is also a problem with reliable data, especially the heating energy consumption values for energy audits at city scale [Bennett, 1999]. In comparison, the here presented method could be verified by the available annual heating energy consumption values for all buildings of the analyzed area.

The use of 3D city models for urban scale simulations is shown in the presented approach and can be regarded as useful. Nevertheless, the models need to be generated in a semantically enriched way and according to a specific ontology (e.g. CityGML). Purely geometric models would not satisfy the information demand of simulation tools in order to produce reasonable results. The connection to thematic and semantic information is essential. In the authors view the geometrical models are widely available as many municipalities already produced this kind of models. Not with the main intention to use them for simulation of course, but they might be used as a basis for a semantically enriched model. Some municipalities already have semantically built models based on CityGML and the integration of additional information in these cases

is much easier. Nevertheless, there is still a lot of research necessary in order to find out which information needs to be linked to the models in terms of simulation input data, in which way this information can be linked and how the interfaces to the simulation tools can be realized. However, the presented approach outlined the feasibility of connecting 3D city models/3D GIS with simulation tools and further research into this field appears to be sensible.

CONCLUSIONS

This paper presented a method of forecasting the heating energy demand at city-scale in order to improve the urban energy management of the area of Scharnhäuser Park. One primary goal of this research work was to test how effectively a very simple 3D model could estimate the heating energy use of the existing buildings. Two models have been tested and verified by the comparison of their results against the actual heating energy consumption of the buildings as measured from actual utility bills. Both of them occurred suitable to forecast the heating energy demand at city-scale. The only advantage of the Model 2 in comparison to Model 1 is the possibility to validate the user behavior related parameters like set-point temperature, internal heat gains, solar gains (different shadow effects), air change rate and length of heating. In case of Model 1 only the set-point temperature can be validated.

The results of the heating energy consumption are already published via Web Application of the POLYCITY project, as a GIS-map of Scharnhäuser Park. It is also planned to publish the saving potential regarding the heating energy consumption to make the residents aware of the sustainable urban development in their city.

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