Universität für Bodenkultur Wien
University of Natural Resources and Life Sciences

Department of Economics and Social Sciences
Institute for Sustainable Economic Development

A GIS-Based Method for Predicting Hourly Domestic Energy Need for Space Conditioning and Water Heating of Districts and Municipalities

Master Thesis

submitted by

Ramirez Camargo, Luis Eduardo

Supervisor:	Schmid, Erwin, Univ. Prof. Dipl.-Ing. Dr.
Co-Supervisor:	Schmidt, Johannes, Dipl.-Ing. Dr.
Supervisor (external):	Dorner, Wolfgang, Prof. Dr.

Vienna, November 2012

Acknowledgements

I would like to deeply thank Prof. Dr. Wolfgang Dorner for the great support, advice and motivation he provided me with, and for welcoming me at the Technology Campus Freyung of the University of Applied Sciences Deggendorf. Furthermore, I want to thank Dr Johannes Schmidt and Prof. Dr. Erwin Schmid for their help and advice after and during the process of writing this thesis.

I would like to especially thank Christopher Young and Nadine Pirker for the invaluable support and for proofreading my texts. Also, I would like to thank all the people at the TC Freyung for the feedback, the programming tips, their permanent help and hospitality.

Finally, none of this would have been possible without the love and patience of my family and friends. Sincere thanks go particularly to Cris, my mother, Juliana, Katrin, Werner Eckert and Werner Kvarda.

Abstract

This thesis presents a method to predict the hourly domestic energy need for space conditioning (SC) and water heating of the domestic buildings (DHW) of German administrative units on the sub-regional level (districts and municipalities).

The core of the method is a Resistance-Capacitance model, which is able to predict the hourly domestic energy need for SC of individual buildings based on limited input data and with low computational demands. The required data concerning the physical characteristics of the buildings are obtained from buildings typologies. The differences in energy need of every single building due to human occupancy patterns are considered by using a stochastic occupancy model. Geographic Information Systems (GIS) data is used in order to classify the individual buildings into the different typologies.

The results show an improvement in the way that ground and peak loads of heating/cooling are predicted for administrative units on the sub-national level. Furthermore, the geo-referenced results provide a solid information basis for energy use plans, climate protection plans or in the early planning stages of district heating/cooling networks or Combined Cooling/Heat and Power (CHP or CCHP) communal investment initiatives.

Reliability and robustness of the method are tested. A case study analysis with a Bavarian municipality shows the ability of the method to predict the hourly domestic energy need for SC and DHW of a large building stock. A sensitivity analysis based in a regression technique has been used to test the logic and robustness of the method, and to corroborate the importance of the input variables. The results of the analysis show that the method is able to reproduce typically observed patterns, that the input variables pose considerable explicatory value, and that the method is able to handle a variety of situations with a limited loss of accuracy.

Keywords: domestic buildings, energy need, GIS, model, sensitivity analysis, space conditioning, sub-regional administrative units.

Kurzfassung

Das Ziel dieser Arbeit ist die Entwicklung eines Verfahrens für die Schätzung des Nutzenergiebedarfs für Raumklimatisierung und Warmwasser von Wohngebäude in Verwaltungseinheiten in Deutschland.

Kernkomponente des Verfahrens ist ein RC-Modell, welches mit wenigen Inputdaten und geringem rechnerischen Aufwand den stündlichen Energiebedarfskennwert von einzelnen Gebäuden liefert. Die notwendigen Daten über die physikalischen Merkmale der Gebäude werden aus Gebäudetypologien entnommen. Die Energiebedarfsunterschiede, welche von der Wohndauer und dem individuellen Verhalten abhängig sind, werden mit Hilfe eines stochastischen Wohndauermodells dargestellt. GIS-Daten werden verwendet, um jedes Gebäude des gewählten Standortes in die verschiedenen Typologien einzuordnen.

Die Ergebnisse des Verfahrens zeigen eine Verbesserung bei der Schätzung von Wärme-/Kühlbedarf bei Grund – und Hochlasten für Verwaltungseinheiten. Außerdem stellt der georeferenzierte Output eine solide Informationsbasis für Energienutzungspläne und Klimaschutzkonzepte dar und kann in der Frühphase der Planung von Fernwärme/-kältenetzen und/oder kommunalen Kraft-(Kälte-) Wärme-Kopplung Initiativen verwendet werden.

Zuverlässigkeit und Robustheit des Verfahrens wurden statistisch getestet. Eine Fallstudie für eine bayerische Gemeinde unterstreicht die Eignung des Verfahrens, den stündlichen Nutzenergiebedarf für Raumklimatisierung und Warmwasser eines großen Gebäudebestands schätzen zu können. Eine Sensitivitätsanalyse wurde durchgeführt, um Konsistenz und Robustheit des Verfahrens zu testen sowie den relativen Effekt von Eingangsgrößen auf das Ergebnis zu bestimmen. Die Ergebnisse der Analyse zeigen, dass (i) das Verfahren typische Muster reproduzieren kann und (ii) eine hohe Flexibilität mit geringem Genauigkeitsverlust aufweist sowie (iii) die Eingangsgrößen einen beträchtlichen explanativen Wert besitzen.

Schlüsselwörter: Wohngebäude, Nutzenergiebedarf, GIS, Modell, Sensitivitätsanalyse, Raumklimatisierung, Verwaltungseinheiten.

Table of Content

List of Figures

List of Tables

Abbreviations

AB: Apartment Blocks

BREDEM: Building Research Establishment's Domestic Energy Model

BREHOMES: Building Research Establishment´s Housing model for energy studies

CDEM: Community Domestic Energy Model

CHP: Combined Heat and Power

CCHP: Combined Cooling, Heat and Power

CREEM: Canadian Residential Energy End-Use Model

CTF: Conduction Transfer Function (method)

DHW: Domestic Hot Water

EEP: Energy and Environmental Prediction model

EM: Engineering models

EnEV: Energieeinsparungsverordnung /energy saving regulation

GIS: Geographic Information Systems

HH: Tower Buildings

LoD: Level of Detail

MFH: Multi-Family Houses

OAT: One-at-a-time

RC: Resistance-Capacitance (model)

RT: Response Transfer (method)

SA: Sensitivity Analysis

SC: Space Conditioning

SCHP : Simple Hourly Calculation Procedure

SFH : Single-Family Houses

SM: Statistical Models

SRCs : Standardized Regression Coefficients

TH: Terraced Houses

TRY: Test Reference Years

TSBI3: Thermal Simulation of Buildings and Installations, 3rd generation

TSBI5: Thermal Simulation of Buildings and Installations, 5rd generation

TUS: Time-Use Survey

UKDCM: UK Domestic Carbon Model

VBA: Visual Basic for Applications

VDI: Verein Deutscher Ingenieure /German Engineers Association

WinSim: Simulation tool for evaluating the influence of windows on heating demand and risk of overheating

1. Introduction

Buildings´ energy requirements account for 40% of total energy consumption in the European Union, the most part of which corresponds to the residential sector (EC, 2003, 2010). The residential sector's energy end-use is mostly related to space conditioning (heating and cooling) and water heating, accounting for 66% and 13% in 2005, respectively (ICCS-NTUA, 2008). Measures to reduce these energy requirements and to change their supply to renewable energy sources are part of the core strategy of the European Union to reduce energy dependency, and to achieve the CO_2 emissions reduction goal by 2020 (EC, 2010).

The identification of potential locations, the planning and implementation of projects and measures for reducing energy demand and promoting renewable energy on the local level require a robust base of information on baseline energy consumption. Specifically, if the interest is centred on developing local energy plans and setting up district heating/cooling networks, planning (heating/cooling) micro-grids or motivating Combined Heat and Power (CHP) communal investment initiatives, the information should be spatially referenced (Rylatt *et al.*, 2003; Kim and Clarke, 2004; StMUG *et al.*, 2011; Howard *et al.*, 2012; Theodoridou *et al.*, 2012) and should be available in a high temporal resolution (VDI, 2008; Pagliarini and Rainieri, 2012; Richardson *et al.*, 2008).

However, this information is usually not properly available or not available at all for the domestic sector, because of reasons such as, decentralized ownership, lack of self interest and expertise in reducing energy consumption, privacy issues limiting the successful collection and distribution of energy data for individual households and the prohibitive costs of detailed sub-metering of households (Swan and Ugursal, 2009). To cope with the lack of information an increasing number of models and methods have been developed to predict the energy use of the domestic sector (Zhao and Magoulès, 2012; Swan and Ugursal, 2009).

Most of the existent models are designed for predictions at the national level with an annual temporal resolution, and are not geo-referenced. Models for predictions in the sub-national level, geo-referenced or with a high temporal resolution are much scarcer and models including these three characteristics are normally only applicable to neighborhoods due to their dependency on very demanding input data.

The objective of this work is the development of a method which allows the user to obtain the spatial distribution of hourly domestic energy need[1] for heating, cooling and hot-water heating over a district or municipality. The method should maintain the input data requirements at a minimum level, and should take into account the variability related with human occupancy. Finally, although the proposed method is applied in a German case study analysis, its applicability for further locations in Europe is also discussed.

The main hypothesis to be tested is that a high resolution spatio-temporal model of the domestic energy need for space conditioning and hot water can deliver robust and reliable predictions for local planning purposes. High spatial resolution (considering buildings as individual objects) and a high temporal resolution (one hour time steps) are compatible and manageable for large building stocks. Robustness and reliability can still be confirmed if only restricted input data is available.

The first part of this thesis is dedicated to a review of modelling options concerning energy demand of domestic buildings. This review focuses on models developed in Europe but also includes relevant examples that could be found in the international context. The third chapter presents the proposed method, divided into two major parts; the first one examines the calculation procedure and the second one the input data. A general scheme for the method is included as well. The fourth chapter presents a test of the model, which includes a comparison of the results with average yearly values of typical German buildings along with sensitivity analysis for the hourly values, and a case study with a German municipality. The final chapter provides conclusions and an outlook for future research.

[1] The focus on energy need, not end energy use, is because this value is more appropriate for conceiving communitarian supply concepts (StMUG *et al.*, 2011). However, this work will also discuss a way to obtain the end energy use without having to resort to further input data.

2. State of the art

Following the classification of Swan and Ugursal (2009), the models for predicting the energy requirements of the residential sector can be divided primarily into top-down and bottom-up models. The first group typically aims at explaining the aggregate estimated national energy consumption of the residential sector by attributing it to characteristics of the entire housing sector. The second group of models concentrates its effort on determining the energy consumption of individual or groups of buildings, for which results are subsequently extrapolated to regions or countries.

Top-down models have been used to investigate inter-relations between the energy sector and a wide range of explicative variables, which allows a further division of such models into two major sub groups: the econometric and technological top-down models. Econometric models are based on economic and demographic factors such as price indexes for energy, gross domestic product or employment rates. Technological models resort to explicative variables inherent in the housing stock, such as appliances ownership trends or housing construction/demolition rates (Swan and Ugursal, 2009).

The principal advantages of the top-down models lie in their simplicity and their use of aggregate (widely available) data, which represents the valuable alternative of having a prompt and general picture of the determinants of energy consumption for the domestic sector on a national scale. However, the lack of detail in both the input data and the results severely affects the applicability of such models in a local context.

On the contrary, bottom-up models rely on detailed input data and are capable of predicting energy requirements for individual end-uses or individual buildings, and are therefore appropriate for detecting specific areas of potential improvement (Kavgic *et al.*, 2010; Swan and Ugursal, 2009; Shorrock and Dunster, 1997). The input data for these types of models includes, inter alia, historical data, climate conditions, geometric characteristics of the dwellings, materials and quality of the building´s envelope, appliances and equipment, type of energy source, occupancy schedules and occupants´ behavioural factors, i.e. the rate of ventilation or the desired heating set point (Zhao and Magoulès, 2012; Kavgic *et al.*, 2010; Swan and Ugursal, 2009).

Based on the required input data, employed technique and the level of detail, it is also possible to divide the bottom-up models into different groups. Swan and Ugursal (2009) propose a division between Statistical Models (SM) and Engineering Models (EM), which corresponds to the statistical based and building physics based models proposed by Kavgic *et al.* (2010), who also proposed a third group of hybrid models, where SM and EM approaches are used together .

The SM approaches offer three principal advantages. Firstly, they do not require detailed data concerning individual buildings. The necessary input data usually originates from billing data and simple survey information (Kavgic *et al.*, 2010; Swan and Ugursal, 2009). Secondly, these models rely mostly on regression techniques, which benefit from several decades of intensive development due to their broad popularity in other fields of study. Thirdly, these models are able to discern the effects of occupant behaviour, which have been found to be a key aspect for determining energy need and consumption (Pilkington *et al.*, 2011; Haldi and Robinson, 2010; Andersen, 2009; Paauw *et al.*, 2009; Page, 2007; Wood and Newborough, 2003; Papakostas and Sotiropoulos, 1997).

However, the SM approaches also present several disadvantages. These models do not provide much data; they depend entirely on historical consumption data, require large samples, they usually have to deal with multicollinearity and are not capable of assessing the impact of new technologies or further energy conservation measures (Kavgic *et al.*, 2010; Swan and Ugursal, 2009). Due to these shortcomings and especially the latter of these, the SM approaches are not the most appropriate ones for developing plans on the local level, where the objective is to test alternatives for reducing energy demand and to promote new energy sources.

The final class of models i.e. the EM are based on the physical characteristics of buildings, and therefore do not require historical data for predicting energy need or consumption of a building in a moment in the past, the present or the future. This approach usually relies on the use of a representative housing stock, and on the utilization of a building-energy calculation method to predict the energy use of every type of building from the selected representative housing stock (Kavgic *et al.*, 2010; Swan and Ugursal, 2009; Aydinalp-Koksal and Ugursal, 2008). The physics based bottom-up models also offer high flexibility for modelling and testing the different types of thermal envelopes of the buildings, different technologies for heating or cooling production and alternative scenarios related to changes in climate and occupancy behaviour (Cheng and Steemers, 2011).

The high potential of the building physics based models for supporting policy making and strategic development is widely recognized, due to their flexibility and level of detail. Nevertheless, the drawbacks of this approach should not be neglected. This type of model requires a large amount of technical data and high computational capacity (Kavgic *et al.*, 2010) in order to obtain accurate results from the building energy calculation method. These models also do not determine human behaviour endogenously but rely on external assumptions, poorly describe societal and market interactions, and disregard any relation between energy use and macroeconomic activity (Kavgic *et al.*, 2010; Natarajan *et al.*, 2011). This is explained by EM´s focus on the physical characteristics and performance of buildings and technologies.

Despite the drawbacks, the building physics based models are widely used in the international context and are also the starting point for this thesis. It has been found that most of the scientific peer reviewed publications concerning these models are related to the UK. The review of the UK experience has shown further shortcomings regarding the EM and the absence of models that are designed to be both, geo-referenced and carried out in high temporal resolution.

The Building Research Establishment´s Housing model for energy studies (BREHOMES), the Johnston Model, the UK Domestic Carbon Model (UKDCM), the DECarb Model and the Community Domestic Energy Model (CDEM) are five remarkable bottom-up building physics models for the UK housing stock. All these models share a version of the Building Research Establishment's Domestic Energy Model (BREDEM) as core calculation and have been repeatedly the object of study and criticism. Kavgic *et al.* (2010) considered that the most significant limitations with these models are their lack of transparency and the fact that they do not test the effects of uncertainties. Cheng and Steemers (2011), following the argument of Shorrock and Dunster (1997) affirm that these models are also limited by their resolution of spatial coverage. I.e. the reviewed models are designed for the national level and may agree with aggregate statistics at this level but are not capable of accurate predictions at the sub-national level (e.g. regions, cities, districts and municipalities). The finer the spatial resolution, the more speculative are the predictions (Shorrock and Dunster, 1997). Natarajn *et al.* (2011) strongly criticise the difficulties that BREHOMES, UKDCM and DECarb present for including emerging and future datasets.

Furthermore, none of these models were developed to deliver spatially referenced results, and the highest temporal resolution taken into account was months (UKCDM, DECarb and CDEM). Other existent bottom-up models for the UK, also based on building physics, addressed spatial referencing by using Geographic Information Systems (GIS), and linked energy requirements to single buildings or post codes. Rylatt *et al.* (2003) have proposed a GIS-based method that also uses the BREDEM calculation engine, and provides estimations on a monthly basis. They do not emphasize the use of GIS for making a spatial representation of energy use or CO_2 emissions, but focus on the advantage of using GIS (combined with building typologies) to satisfy the data input requirements of the BREDEM by using reduced data sets (Rylatt *et al.*, 2003).

Jones *et al.* (2001) developed the Energy and Environmental Prediction (EEP) model, which is GIS-based and includes an energy use calculation methodology also based on a version of BREDEM. The EEP relies on several sub-models, which allow for the prediction not only of energy use and emissions of domestic buildings, but also of non-domestic buildings, transport systems and industry on a yearly basis (Jones *et al.*, 2001). A further development from the EEP approach was the introduction of a public health sub-model. It uses GIS tools to derive the required data for its own adaptation of BREDEM, and generates a geo-referenced heat vulnerability index for London on a yearly temporal scale (EPSRC, 2009; Mavrogianni *et al.*, 2009).

The valuable contribution of GIS spatial data to support strategic decision-making concerning the fostering of better energy efficiency strategies and adoption of clean energy systems was also recognised and exploited for developing the EnTrack web-based information exchange platform (Kim and Clarke, 2004). The platform was tested by generating a CHP feasibility map for the urban area of Glasgow using the yearly energy use values of single buildings (Ibid). The platform can work with measured or predicted data and therefore does not actually include its own calculation method for predicting the energy use of buildings (using a constrained number of building typologies and predicting their energy by using BREDEM is also not out of the range of possibilities).

Unfortunately, none of the reviewed GIS-based models offer a high temporal resolution (at least one hour time steps), and almost all of them rely on the same limiting factor as the considered non GIS-based models i.e. the use of versions of BREDEM as the core calculation engine. Having a high temporal resolution results in a more complex situation that requires a significantly larger amount of information related to climate conditions and human occupancy and behaviour. As a consequence, this kind of estimation is normally used for the detailed modelling of single (new) buildings mostly in the non-residential sector.

An example of predicting energy use for a large number of domestic buildings on high temporal (one minute time steps) resolution was developed by Richardson *et al.* (2010). They compared the (stochastically) predicted data with measured information from 22 dwellings in the East Midlands in the UK, showing that both data sets had similar statistical characteristics (Richardson *et al.*, 2010). Although, the authors developed an innovative and usable (also freely available) alternative for modelling human occupancy[2] and use of appliances that is considered later on, the model has been

[2] The occupancy model was already presented in Richardson *et al.* (2008)

developed to predict electricity use, not energy use for space conditioning and water heating. Additionally, the authors do not consider geo-referencing the predicted values, although there is no apparent restriction which goes against implementing this model in a GIS-based approach.

Building physics based bottom-up models for predicting energy-demand in other countries are also examined. Three out of four models reviewed in Kavgic *et al.* (2010) present similar characteristics to the UK models. The Canadian Residential Energy End-Use Model (CREEM), the North Karelia, Finland model and the Hens, Verbeeck, and Verdonck (2001) model for the Belgian residential sector all possess the same shortcomings: they lack transparency, do not test the effects of uncertainties, are limited by the resolution of spatial coverage, have problems when introducing future data sets, are not developed for being geo-referenced and finally, use calculation methods that generate yearly predictions. The Fourth model has been developed for the US building stock and presents an important singularity. Compared with other models, the core calculation method, i.e. the DOE-2.1 simulation tool, delivers detailed hourly load shapes (Kavgic *et al.*, 2010). This characteristic has been introduced, bearing in mind that the results can be used to select energy efficiency program needs, evaluate energy pricing alternatives or examine alternative energy service contracts (Huang and Brodrick, 2000).

Models for Belgium, the Czech Republic, Denmark, Germany, Greece, Italy and Slovenia have been compiled in the frame of the TABULA project, an EU project conceived to develop buildings typologies for thirteen EU members (Loga *et al.*, 2012). These models demonstrate the usability of typologies to estimate energy consumption and to identify energy saving potentials of national residential building stocks (Ibid). The models used nationally defined calculation engines, which in all cases except for Belgium could be verified to be similar to the seasonal or monthly calculation of the EN ISO 13790:2008. The calculation has been adapted depending on the input data's availability, and to fit with average national information. These models do not offer any advantage over other models previously described, but the information that is now available on national typologies could give valuable input for further model development and applications.

Most international publications not related to the UK do not offer any further contribution to a GIS-based approach beyond what has been already presented for this case. However, Strzalka *et al.* (2011) proposed an approach based on 3D maps with different levels of detail and on two different calculation engines to predict yearly energy demand for heating on an urban scale. The first calculation engine takes into consideration only the transmission losses through the outer envelope of the building. The second corresponds to the method described in the German standard DIN V 18599, which considers the entire energy balance of the building (Strzalka *et al.*, 2011). A case study was carried out within an outer district of Stuttgart, where the predicted values under standard assumptions (heating set-point at 20°C, air exchange rate of 0,5 l/h and internal heat gains of 5 $\mathrm{W/m^2}$) presented a good correlation with measured values. The results are more accurate when using the second calculation engine and also when the dimensions of the buildings and u-values used as input correspond exactly to the actual values of the building. Additionally, the relevance of human occupancy and behavior has been recognized as a decisive factor that should be treated in more detail. Nevertheless, the model has been applied to a very homogeneous sample of buildings constructed between 2002 and 2008, which does not permit the affirmation of much about its applicability to the whole range of buildings that exist in the German housing stock. Moreover, though 3D maps seem to be a promising source for this kind of study, the very simple ones with level of detail one (LoD1) still have prohibitive costs if the intention is to model a city. Additionally, 3D maps with a higher level of detail (LoD2 or LoD3), which have shown to provide more accurate results, are still scarce.

In the field of high temporal definition models, the international focus is also on individual buildings. The German Engineers Association (VDI) for example, defines a methodology for determining the energy load profile of single family houses on a one minute time step basis, and of multi-family houses on 15-minute time step basis. This is applied to space-heating, warm water and electricity and is based on the actual or predicted yearly end energy use (VDI, 2008). Applying this methodology to several buildings helps to represent how energy demand changes throughout a whole day on a very detailed basis. Nevertheless, it also reproduces the same pattern for all buildings of the same type, and therefore it misrepresents the differences in the demand patterns of the households.

Another attempt was made by Pagliarini and Rainer (2012), who proposed a non-linear multivariate regression approach incorporating climate data and the monthly energy consumption, to restore the buildings' hourly space-heating and cooling loads. Although this approach could be quite useful and accurate when energy bills are available, a lack of availability of bills would oblige those making the calculations to predict the energy use. However, it does not make any sense to model energy use on a monthly basis, and then to restore the hourly values when a direct prediction of the hourly data is possible. The restoring of the results of other models already mentioned are discarded because of their previously mentioned shortcomings.

As can be seen from the reviewed models, the generation of hourly and geo-referenced values for the energy use of domestic buildings that could support strategic decision-making about district heating/cooling networks, (heating/cooling) micro-grids or other projects such as CHP communal initiatives at the local level requires further development. This work will build on the strengths of some of the presented approaches with the aim of formulating a method that encompasses these desirable features.

3. The proposed method for predicting hourly domestic energy need for space conditioning and water heating of districts and municipalities

Following most of the bottom-up building physics based approaches, the proposed method consists of two major components: a buildings stock and a calculation procedure for predicting the energy demand. The objective is that the calculation procedure and the required input data provide enough flexibility to model the building stock of any district, municipality or administrative division in the sub-national level. Aiming to accomplish this calculation without relying heavily on a large amount of input data, an approach based on buildings typologies is used. These typologies will serve as source of information. For example, the u-values of the components of the buildings´ envelope, and the g-values of windows, which otherwise require very demanding surveys to be conducted.

The method is explained in two parts. The first includes all the alternative calculation procedures considered, plus the arguments for selecting the preferred option and the calculation procedure itself. The second is dedicated to the input data and its different sources. To close the chapter, a final section is dedicated to the general scheme for the method.

3.1. The calculation procedure

A fundamental part of the proposed method is the calculation procedure for predicting the energy need of individual buildings for space conditioning (SC) and domestic hot water (DHW). This calculation should be able to work with minimal information requirements and be capable of delivering results on a one hour time step basis. It should also be robust and flexible enough to be applicable to different regions under different climatic conditions, and able to integrate new emerging data sets.

There are building physics based calculation procedures for predicting energy need, energy use and primary energy demand. These last two outputs usually include a calculation or an assumption about energy need for DHW. However, this is not the case for methods calculating energy need; these methods are usually concentrated on SC. Considering that the objective of this thesis is the energy need for both SC and DHW, the review of alternatives is divided into two steps. Firstly, an alternative for SC is selected independently of its originally predicted objective, and secondly a calculation procedure for energy need for water heating is incorporated or adapted depending on the characteristics of the procedure selected in the first step.

3.1.1. Selection of the calculation procedure for Space Conditioning

Most of the calculation engines used for large stocks of buildings have a temporal resolution of years or months (see chapter 2). These calculation engines are not thought to model dynamic processes and usually use a reduction factor to consider evening and weekend setbacks, and a gain utilization factor to reflect the thermodynamic behavior of the buildings. Changing the calculation procedure to a dynamic one allows documenting the behavior of the building in a much more detailed way, and to incorporate non-deterministic behavioral and climatic patterns instead of the average predefined profiles which are recurrent in non-dynamic models.

Entirely dynamic calculation procedures, such as the response transfer (RT) methods or the conduction transfer function (CTF) methods used usually for exhaustive simulations, require and generate a significant amount of data. Very detailed input data about the physical characteristics of the buildings and a high computational capacity are necessary (Zhao and Magoulès, 2012; Kämpf and Robinson, 2007; Peng and Wu, 2008), and results with one second or one minute time step resolution could be achieved. However, neither the required input data can be obtained for a large amount of (old) buildings without incurring detailed and very demanding surveys, nor is the temporal definition required to be so high because of the relative stability of the thermal conditions of a building when compared to the volatility of e.g. electricity demand. Additionally, the climate data, a decisive input parameter, is mainly available on an hourly basis. Taking these factors into account, a simplified one hour time step calculation is applied.

There are several alternative procedures or strategies that can be used to obtain one hour time step predictions relying on reduced input data. Firstly, it is possible to use well established existing software, which is usually used for very precise simulation of the thermal conditions of buildings (also based on RT or CTF methods), and to simplify the buildings´ models to the available amount of data. This is e.g. the alternative selected by Huang and Brodrick (2000). They used the DOE-2.1 software to deliver hourly load shapes of typical buildings and to aggregate them to obtain the energy demand of the whole US building stock. However, this alternative should be discarded because, despite the existence of freely available and widely documented options, the use of a software packages like

DOE-2.2[3], eQUEST[4] or ESP-r [5] means that the core of the proposed method becomes a "black box", and any adaptation probably requires the accomplishment of more work than required to develop or modify a more simple calculation method which is not already incorporated into a program and requires less computational capacity.

A second alternative can be found e.g. in Déqué, Ollivier and Poblador (2000). They developed a so called "grey boxes" model to reduce the number of input parameters to about ten, and in a test with typical French domestic buildings their predictions were barely different to the ones that could be obtained with highly precise and demanding models (Déqué *et al.*, 2000). This alternative has also been discarded however, due to the lack of general applicability that exists because of the strong dependence of the reduced model on the cases from which it was derived (Kämpf and Robinson, 2007).

The last alternative that was considered corresponds to a group of model simplification techniques, which includes the harmonic method and the resistance-capacitance (RC) network methods. The first method was originally proposed by Mackey and Wright in 1944 to calculate the heat gains through building walls and roofs. The idea was to propose a thermal conduction equation that could be solved by presenting boundary conditions as periodic functions (climatic harmonic). However, there have been different arguments regarding the level of efficiency of this model. Peng and Wu (2008) affirm that the harmonic method calculations are complicated, inaccurate and inefficient, and offer an improved version of these by including a thermoelectricity analogy in the core of the method. Additionally, Kämpf and Robinson (2007) do not completely agree with the level of complexity of the method, but recognize that the necessary assumption of a repeated climatic harmonic leads to inaccurate predictions, and also outlines that methods based on an electrical analogy represent a superior alternative.

The second type of simplification techniques rely on making analogy of heat transfers to electrical currents. They represent temperatures (inside and outside buildings and rooms) with nodes, link the nodes with resistors to represent heat flows, and are able to include the bodies´ thermal inertia by using the analogy to capacitances. The RC network methods are capable of representing individual sections such as walls, roofs or windows, entire buildings and theoretically even neighborhoods[6].

[3] the current version of DOE-2.1, available at http://doe2.com/DOE2/index.html (accessed:07/04/2012)
[4] User friendly version of DOE-2.2, available at http://doe2.com/equest/ (accessed:07/04/2012)
[5] result of more than three decades of development by a international collaboration community, available at: http://www.esru.strath.ac.uk/Downloads/downloads.htm#ESP-r (accessed: 10/05/2012)
[6] Page *et al.* (2008), Page (2007) and Kämpf and Robinson (2007) make reference to a project, called SUNtool, which uses the RC approach together with other stochastic models related to occupant behavior for modeling

These methods are considered efficient, simple and accurate; even though modeling a building increased the number of nodes, they could be lumped and the method would remain simple (Peng and Wu, 2008; Fraisse *et al.*, 2002; Kämpf and Robinson, 2007).

The RC network methods for representing the thermal characteristics of buildings have been the object of study and development over a long period of time. Examples can be traced more than four decades back into the past (Dewson *et al.*, 1993). For the purposes of this work, the search for alternatives is constrained to state of the art methods (developed in the last decade) which are well documented and are conceived to represent energy transfers of entire buildings. Four methods that fulfill these requirements are considered:

The first option was proposed by Fraisse *et al.* (2002), who generated a model for a one zone building making a detailed description of walls, windows, ceilings and air exchanges. They made a special effort, representing and integrating a heating floor (hydraulic or electric). The detailed description of the conductive, convective and radiative exchanges of every single component resulted in 40 nodes that should be considered, i.e. 40 differential equations that should be solved at the same time for every time step (Fraisse *et al.*, 2002). The accuracy of the model was tested by comparing its output with measured data collected in an experiment in a real classroom located in the “Ecole Supérieure d’Ingénieurs de Chambéry”, where both modeled and measured data showed slightly different results. However, the robustness and flexibility of the model were not discussed and no further sources using the same (entire) model were found.

The next considered option was proposed by Nielsen (2005). In this case the author develops a three resistance two capacitances (3R2C) model, which was able to generate results comparable to the ones obtained with detailed simulation tools by using input data equivalent to one used for the simplified monthly calculation procedure consigned in EN 832 (Nielsen, 2005). This model is based on the simulation tool for evaluating the influence of windows on heating demand and risk of overheating (WinSim) introduced by Schultz and Svendsen (1998). The core of WinSim is a two node with two resistances and two capacitances (2R2C) room model with the main thermal mass located in the internal construction. The accuracy of the results obtained with WinSim was validated satisfactorily against the detailed thermal simulation tool “Thermal Simulation of Buildings and Installations, 3rd generation” (TSBI3) of the Danish Building Research Institute (DBRI) when simulating

---

the energy flows of entire neighborhoods to support sustainable urban planning. Unfortunately, the web page of the project is no longer available http://www.suntool.net.
However, at least a part of the same consortia that participate in SUNtool is now working on the development of a software called CitySim. This software is said to be the successor to SUNtool. This is planned in order to integrate sub models for electric appliance usage, transport and waste, and to take into account the energy flows between the sub-models (Robinson *et al.*, 2009). Also in this case the software itself could not be found.

a simple model of an office. The major contribution of Nielsen (2005) is the inclusion of a temperature node for the internal surfaces (θ_s). This addition makes the model not just suitable for evaluating the influence of windows on heating demand, but also for evaluating the energy demand, for heating and cooling, and the quality of the indoor environment in terms of temperature. This model was satisfactorily validated by comparing the results of the simulation of a reference office building located in Copenhagen with those obtained through the detailed building simulation tool Bsim (Nielsen, 2005), which´s core thermal simulation tool "Thermal Simulation of Buildings and Installations, 5[rd] generation" (TSBI5) is a slightly enhanced version of the TSBI3 (Grau and Wittchen, 1999).

The third option is an extension of Nielsen´s (2005) model made by Kämpf and Robinson (2007). This five resistance two capacitances (5R2C) alternative presents improvements for the way in which external surface radiant- and internal and external convective energy exchanges are taken into account, and for the placement of the capacitance in multilayered walls. The most notorious changes to achieve these improvements are the inclusion of a node for the outside wall temperature (θ_{os}) linked to the wall temperature node through $H_{tr,em}$, i.e. the conductance of the external part of the wall, also linked to an additional outside temperature node (θ_e) through $H_{tr,e}$, which represents the conductance of the thin layer of air at the external wall surface and includes conductive and convective terms (Kämpf and Robinson, 2007). Additionally, the internal energy gains due to the presence of people and machines (L_{air}) were divided between a radiant heat flux (L_r) that affects only the internal surface temperature node (θ_s), and a convective part (L_c) that directly affects the room temperature node (θ_{air}).

The second and third option, as well as the basic original model of Schultz and Svendsen (1998) are presented in

Fig. 1 and the additions between every version are highlighted in red.

The inclusion of a conductance of the external part of the building constructions and, in general, a (second) link to the exterior in Kämpf and Robinson (2007) also contributes to correcting a shortcoming resulting from a simplification consciously adopted by (Schultz and Svendsen, 1998) and inherited by the model of Nielsen (2005). Schultz and Svendsen (1998) locate the main thermal capacity in the internal constructions and neglect the thermal mass of the building envelops, which simultaneously excludes its heat transfer to the outside. They argue that as long as the internal heat transfer coefficient is large compared to the heat loss coefficient, this assumption does not have major effects on the modeled results. This argument is appropriate when considering single rooms or offices, i.e. spaces where the internal wall area is larger than the external wall (envelope) area, but it loses validity when the objective is to model a whole building, and even more a one zone building with all of the construction´s parts interacting with the exterior. Thus, the inclusion of a link between the external part of the building's construction and the outside represents a gain in the applicability of the model.

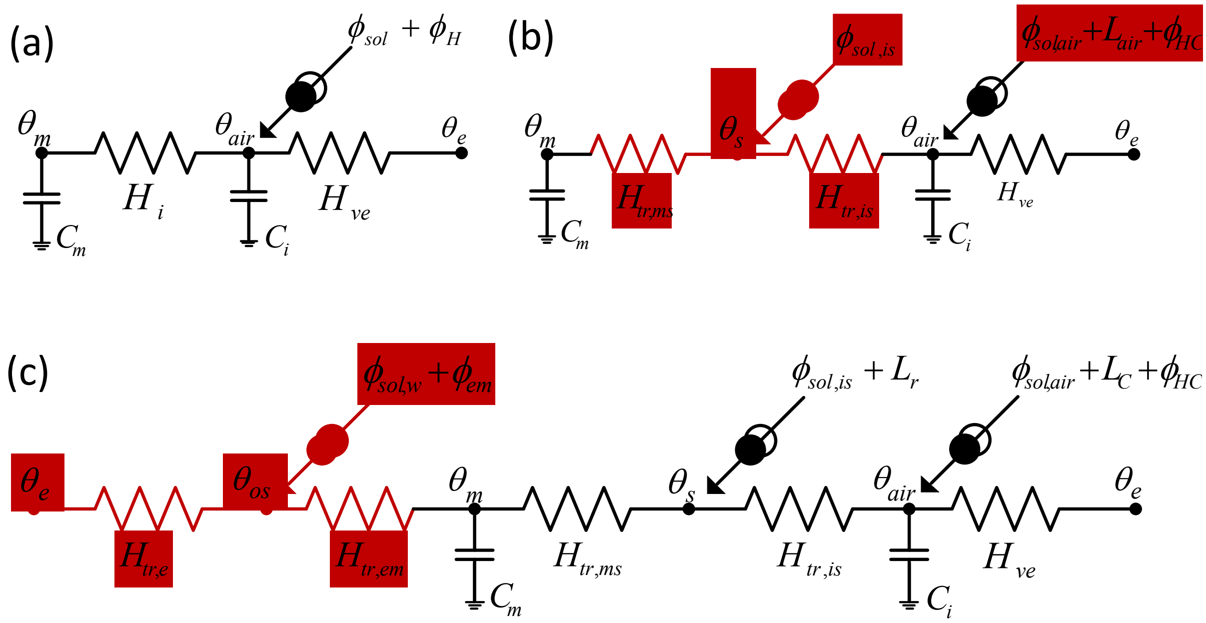


Fig. 1. (a) The 2R2C model of Schultz and Svedensen (1998) (b) the 3R2C model of Nielsen (2005) and, (c) the 5R2C model of Kämpf and Robinson (2007)

Additionally, Kämpf and Robinson (2007) have widened and generalized the applicability of the model by contemplating the inclusion of several zones. They connect the internal air nodes (θ_{air}) of two zones via a separating wall resistance and divide its thermal inertia between the neighboring zones capacitances. They also leave open the possibility of considering an interzonal airflow coupling, which can be included as a part of the separating wall resistance (Kämpf and Robinson, 2007).

Two types of validation methods were implemented by Kämpf and Robinson (2007). Firstly, they carried out a code check by implementing the model in MATLAB and in C++ and compared the results. Secondly, they compared both, the one zone case and n-zones case with the software ESP-r and obtained satisfactory similar results for several different types of simplified rooms, which, among others, do not include internal heat gains due to human presence or appliances.

The fourth RC model considered is the "simple hourly calculation procedure" (SHCP) explained in the EN ISO 13790:2008. It is defined as a five resistances and one capacitance (5R1C) model (see Fig. 2) and is thought to predict the energy needs for heating and cooling of one zone buildings, and n-zones buildings with and without adiabatic boundaries. This model is not explicitly based on any of the already presented alternatives, but shares similar characteristics. Relevant examples of similarities are listed below:

- A temperature node for the internal air temperature and a node for the temperature of the internal surfaces are considered.

- The shortcoming of the Schultz and Svendsen (1998) proposal is also coped with by introducing a link between the temperature of the constructions and the outside temperature.

- The model can be run with input data equivalent to the one used for the ISO 832, which is the predecessor of the EN ISO 13790.

- An extension for integrating n-zones is considered.

Several differences can also be recognized and are listed below:

- In contrast to Kämpf and Robinson (2007), there is no explicit differentiation between the outside wall temp and the outside ambient temperature, and therefore a resistance for representing the conductance of the thin layer of air at the external wall surface has not been included.

- The conductance of the constructions has not just been explicitly divided between an internal and an external part as in Kämpf and Robinson (2007), but also an explicit differentiation between the opaque building elements and not opaque building elements such as doors, windows, curtain walls and glazed walls was made. In Kämpf and Robinson (2007) there is also theoretically such a differentiation, but this is not presented in the graphical representation of the electronic analogy of the model.

- The conductance through windows and ventilation does not necessarily link the indoor air temperature node with the external temperature node, but a supply temperature node was included in case it is considered relevant for the calculation of the energy need to directly include a modification in the temperature generated by a pre-heating, pre-cooling or heat recovery system.

- There is no an explicit representation of the heat capacity of the air and furniture connected to the indoor air temperature. Nevertheless, the heat capacity of the air is still considered for the calculation of the conductance through windows and ventilation.

- The effect of internal gains due to appliances and human occupancy is divided between the indoor air temperature node, the node for the temperature of the internal surfaces and the opaque building elements temperature node.

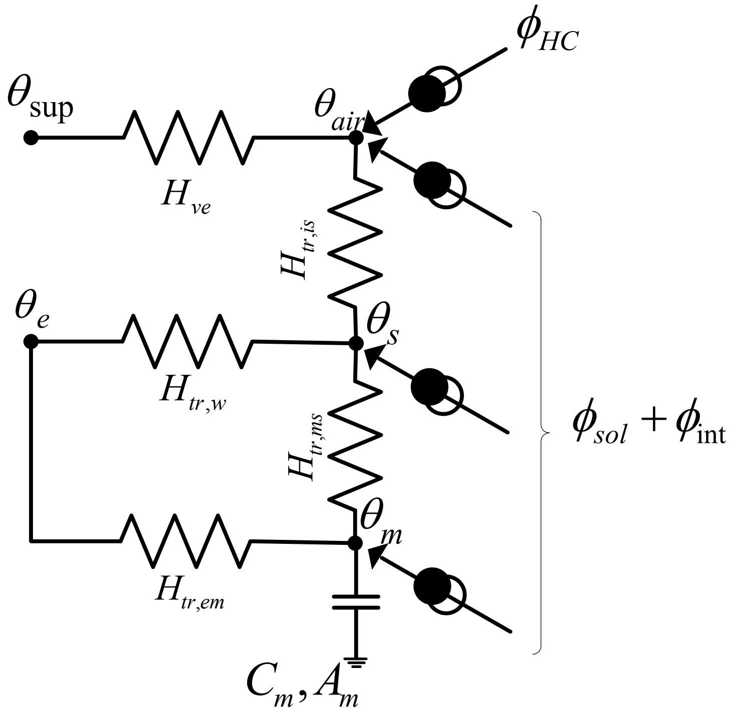


Fig. 2. The Simple Hourly Calculation Procedure (SCHP) as an equivalent 5R1C electrical circuit (CEN, 2008)[7]*.*

Due to the relevance of the international standard, the model has not just been validated by the authors, but also by other members of the scientific community. The authors tested it by following the international standard EN 15265, and the procedure satisfactorily fulfills the required criteria. These criteria are constrained to a limited number of test cases with only one location (Paris, France) and cover only monthly results. I.e., the authors suggest considering the hourly results just as illustrative (CEN, 2008). Additionally, Kokogiannakis *et al.* (2008) tested the procedure against results obtained with software packages ESP-R and EnergyPlus and the monthly procedure, which can also be found in the Standard, for several configurations of office buildings for the weather conditions of different European cities, including Amsterdam, Aberdeen and Athens and with different internal

[7] the nomenclature is consistent with the one used in (2008) but the iconology corresponds to the one used in the previous section.

heat gains and ventilation schedules. The cumulated yearly energy need predictions are divided between heating and cooling and classified into different classes. In general the hourly method generates satisfactorily similar results to the ones obtained with the detailed simulation programs, but the differences in the calculation of energy for cooling presented a higher variability than that concerning heating (Kokogiannakis *et al.*, 2008).

Several calculation alternatives able to generate one hour time-step profiles have been presented and discarded because of undesirable characteristics. More attention was paid to RC network methods due to their simplicity which does not necessarily compromise accuracy or generality, the low input data requirements and the theoretically wide range of application. Nevertheless, selecting the most appropriate of the RC network methods requires a stricter comparison of how the methods cope with these criteria. The results of this comparison are listed below:

a) Although the first alternative can consider more detail, it requires more computational capacity and more input data to make the predictions. This requires solving 40 nodes compared to 4 or 5 that are necessary for the other alternatives. And, unfortunately a lumped version was not presented by the authors.

b) The first alternative is the only one tested with empirical data, and the results are valuable if the interest is to model in detailed complicated constructions such as heating floors. However, the range of applicability of the model (other types of buildings, other climatic conditions, assumptions in case of there not being any available data) was not even discussed by the authors and no further examples using the entire model could be found.

c) The third alternative is superior to the second one because the correction of one of the important shortcomings though maintaining the same core makes it adequate for a wider range of applicability.

d) The second, third and fourth alternatives were satisfactorily validated with detailed thermal simulation programs. This does not leave much room to select a method for their accuracy, because that would require a validation of the validation, which is far beyond the scope of this thesis. However, the fourth alternative is the only one that was through a validation process which includes internal gains due to human occupancy and behavior. This is an important characteristic when considering real existent buildings, as is the case of this thesis.

To summarize, statements a) and b) are strong enough arguments to discard the first alternative. The second alternative can be discarded based on point c). But between the third and fourth alternatives, a decision cannot be made directly from d). Although the integration of internal gains due to human occupancy and appliance use is not directly made in the third option, the model was designed to be part of a more complex model able to incorporate this factor (Kämpf and Robinson, 2007). This means that it would be valid to incorporate the internal gains and make a further validation of the whole model, but that would lead to the situation in which a validation of the validation is required to compare accuracy between the two alternatives. Considering this, the selection of the method should be based on other criteria.

The fourth alternative offers a group of advantages which are not present in the third option, and which are also are important for the objectives of this thesis. In the EN ISO 13790:2008, a significant number of possible situations concerning the input data were explicitly considered as well as the proposed alternatives to cope with them. These considerations represent a level of robustness and flexibility for the calculation method that has not yet[8] been offered by the third alternative. Additionally, the method in the Standard is the result of an international consensus of well known institutions, and moreover is legally secure, which could generate a better reception of the entire proposed method from the wider public. These characteristics have led to the selection of the SHCP as the core calculation method for the method proposed in this thesis.

3.1.2. The customized "simple hourly calculation procedure" (SHCP)

The EN ISO 13790:2008 includes a wide range of alternatives for the input data that could be used for simplification of the SCHP itself. Remaining within the bandwidth of these alternatives preserves the full load of characteristics that have been attributed to the method in the previous section. A customized version of the SCHP[9] is presented below. This version is constrained to the calculation of energy need[10,]. The calculation remains within the bandwidth permitted in the EN ISO 13790:2008, and is customized especially to be used with input data which can be obtained from the typologies of the TABULA project and also the stochastic occupancy model of (Richardson *et al.*, 2008) which are presented and discussed in section 3.2.

[8] The publications concerning the third option do not go that far in the explanation but that does not mean that the method could not be as robust and flexible as the proposed in the EN ISO 13790:2008.
[9] Modifications made by the author are specified. Otherwise the equations are taken from the EN ISO 13790:2008. For coherence with the rest of this thesis, differences in the nomenclature are also possible.
[10] It is equivalent to the "balance at the building level" contained in the standard but without considering the heat dissipated in, or absorbed by, heating, cooling, hot water or ventilation systems.

The entire calculation procedure corresponds to a single conditioned zone building where only sensible heat is considered. The basic operative logic of the procedure is that the energy need for heating or cooling for each hour is obtained by calculating the cooling (negative) or heating (positive) power, $\phi_{HC,nd}$, that should be supplied or extracted to maintain a certain minimum or maximum set-point temperature at the internal air node θ_{air}.

To facilitate the explanation, the calculation has been divided into eight steps. Each step corresponds to a group, or to one of the main variables. The correspondences are presented in a graphical representation of the customized SCHP (see Fig. 3).

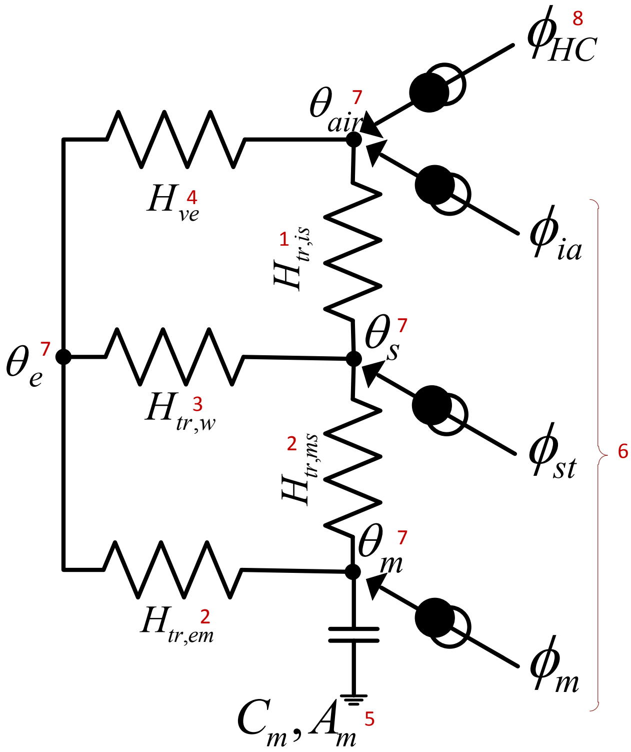


Fig. 3. The Customized SCHP as an equivalent 5R1C electrical circuit based on CEN (2008)[11] and the corresponding calculation steps.

Step 1: Calculation of the coupling conductance $H_{tr,is}$ between the air node (θ_{air}) and the internal surface node (θ_s), that is given in Watts per Kelvin and is defined in equation (1).

$$H_{tr,is} = h_{is} A_{at} A_f \quad [W/K] \tag{1}$$

Where:

[11] the nomenclature is consistent with the one used in CEN (2008), but the iconology corresponds to the one used in the previous section.

h_{is} is the heat transfer coefficient between the air node (θ_{air}) and the surface node (θ_s), in W/m^2K

A_{at} is the dimensionless ratio between the internal surface area and the floor area

A_f is the conditioned floor area, in m^2

Step 2: Calculation of the thermal transmission coefficients of the internal and external part of the opaque building elements $H_{tr,ms}$ and $H_{tr,em}$, which are given in Watts per Kelvin, are defined in equations (2) and (3) respectively. These two terms are the result of splitting the thermal transmission coefficient of the opaque building elements $H_{tr,op}$ which is also given in Watts per Kelvin and is defined in equation (4).

$$H_{tr,ms} = h_{tr,ms}A_m \quad [W/K] \tag{2}$$

$$H_{tr,em} = 1/(1/H_{tr,op} - 1/H_{tr,ms}) \quad [W/K] \tag{3}$$

$$H_{tr,op} = \sum_i b_{tr}A_i\,(U_i + \Delta U_{tb}) \quad [W/K] \quad for \quad i{:}\, walls, roof, ground\ floor \tag{4}$$

Where:

b_{tr} is the adjustment factor used to contemplate the effect of the difference of the external temperature and the temperature of the soil in contact with the ground floor.

A_i is the area of the element i of the building envelope, in m^2

U_i is the thermal transmittance of the element i of the building envelope, in W/m^2K

$\Delta U_{tb,i}$ is the thermal bridge surcharge on the element i of the building, in W/m^2K

$h_{tr,ms}$ is the thermal transfer coefficient, in W/m^2K

A_m is the effective mass area, in m^2

Step 3: Calculation of the thermal transmission coefficient of the lightweight building elements (doors and windows) $H_{tr,w}$ which is given in Watts per Kelvin and is defined in equation (5).

$$H_{tr,w} = \sum_i A_i \,(U_i + \Delta U_{tb}) \quad [W/K] \quad for \quad i: doors, windows \tag{5}$$

Where:

A_i is the area of the element i of the building envelope, in m^2

U_i is the thermal transmittance of the element i of the building envelope, in W/m^2K

$\Delta U_{tb,i}$ is the thermal bridge surcharge on element i of the building, in W/m^2K

Step 4: Calculation of the heat transfer coefficient by ventilation $\mathrm{H_{ve}}$ which is given in Watts per Kelvin and is defined in the equation (6).

$$H_{ve} = H_{ve,act} + H_{ve,inf} \quad [W/K] \tag{6}$$

Where:

$\mathrm{H_{ve,act}}$ is the heat transfer coefficient by ventilation due to active ventilation in W/K and defined in the equation (7).

$\mathrm{H_{ve,inf}}$ is the heat transfer coefficient by ventilation due to infiltration, and is defined in equation (8).

$$H_{ve,act} = \rho_a c_a q_{ve,act} f_{ve,t} \quad [W/K] \tag{7}$$

$$H_{ve,inf} = \rho_a c_a q_{ve,inf} \, A_f he_{room} \quad [W/K] \tag{8}$$

Where:

$\rho_a c_a$ is the heat capacity of the air per volume, in $Wh\,/\,(m^3 k)$.

$q_{ve,act}$ is the airflow rate with external air per person, in $m^3/(h\ person)$

$q_{ve,inf}$ is the airflow rate factor with external air, in $1/h$

$f_{ve,t,k}$ is the time fraction of operation of the active ventilation. Where 1 represents open windows for the whole hour and 0 closed windows.

he_{room} is the room height, in m

Step 5: Calculation of the internal heat capacity of the opaque elements of the building envelope, given in Joules per Kelvin and defined in the equation (9).

$$C_m = \sum_i kA_i \quad [J/K] \quad for \ \ i: walls, roof, ground\ floor$$ [12] *(9)*

Where:

k is the internal heat capacity per area of building element, in $J\ /\ (m^2k)$

A_i is the area of the element i of the building envelope, in m^2

Step 6: Calculation of the solar(ϕ_{sol}) and internal (ϕ_{int}) heat gains and their subdivisions ϕ_{ia}, ϕ_m, ϕ_{st} that are given in Watts and defined in the equations (10), (15), (19), (20) and (21) respectively.

$$\phi_{sol} = \sum_k \phi_{sol,k} \quad [W] \qquad (10)$$

Where:

$\phi_{sol,k}$ is the heat flow by solar gains through building element k given in watts and defined in the equation (11).

$$\phi_{sol,k} = F_{sh,ob,k}\, A_{sol,k} I_{sol,k} - F_{r,k}\phi_{r,k} \quad [W] \qquad (11)$$

Where:

$F_{sh,ob,k}$ is the dimensionless shading reduction factor for external obstacles for the effective solar collecting area of surface k.

$A_{sol,k}$ is the effective collecting area of surface *k* given in m^2. In the case of the lightweight building elements, it is defined in equation (12) and for the opaque elements in equation (13).

$I_{sol,k}$ is the solar irradiance, given in W/m^2 of the collecting area of surface *k*, with a given orientation.

$F_{r,k}$ is the form factor between the building element and the sky.

[12] It should correspond to the opaque building elements in contact with the internal air. In this customized version all opaque building elements are in contact with the internal air.

$\phi_{r,k}$ is the extra heat flow due to thermal radiation to the sky from building element k given in W. This flow is not a solar heat gain, but it is included here for convenience and defined in equation (14) for the opaque parts of the building, and is assumed to be 0 for the lightweight components of the building.

$$A_{sol,w} = g_{gl}(1 - F_F)A_{w,p} \quad [m^2] \tag{12}$$

$$A_{sol,op} = \alpha_{S,c}R_{se}U_cA_c \quad [m^2] \tag{13}$$

$$\phi_{r,k} = R_{se,}U_cA_ch_r\Delta\theta_{er} \ [W] \tag{14}$$

Where:

g_{gl} is the total solar energy transmittance of the transparent part of the element.

F_F is the frame area fraction, ratio of the projected frame area to the overall projected area of the glazed element.

$A_{w,p}$ is the overall projected area of the glazed element in m^2.

$\alpha_{S,c}$ is the dimensionless absorption coefficient for solar radiation of the opaque building element.

R_{se} is the external surface heat resistance of the opaque building element in m^2K/W.

U_c is the thermal transmittance of the opaque building element that receives solar radiation, in a certain direction in W/m^2K.

A_c is the projected area of the opaque part.

h_r is the external radiative heat transfer coefficient, in W/m^2K.

$\Delta\theta_{er}$ is the average difference between the external air temperature and the apparent sky temperature in $°C$.

The internal heat gains are divided into three main sources as shown below.

$$\phi_{int} = \phi_{int,O} + \phi_{int,A} + \phi_{int,L} \ [W] \tag{15}$$

Where:

$\phi_{int,O}$ is the internal heat flow rate from occupants, given in W and defined in equation (16).

$\phi_{int,A}$ is the internal heat flow rate from appliances, given in W and defined in equation (17).

$\phi_{int,L}$ is the internal heat flow from lighting, given in W and defined in equation (18).

$$\phi_{int,O} = n_{O,act} * \phi_{O,act} + n_{O,sle} * \phi_{O,sle} \quad [W] \tag{16}$$

$$\phi_{int,A} = \frac{n_{O,act}}{n_{O,tot}} * A_f * \phi_{A,act} + \left(1 - \frac{n_{O,act}}{n_{O,tot}}\right) * A_f * \phi_{A,rest} \; [W] \tag{17}$$

$$\phi_{int,L} = \frac{n_{O,act}}{n_{O,tot}} * A_f * \phi_{L,act} \quad [W] \tag{18}$$

Where:

$n_{O,act}$ is the amount of active occupants in the building during the actual calculation hour.

$\phi_{O,act}$ is the heat flow rate from active occupants, given in W.

$n_{O,sle}$ is the amount of sleeping occupants in the building during the actual calculation hour.

$\phi_{O,sle}$ is the heat flow rate from sleeping occupants, given in W.

$n_{O,tot}$ is the total amount of occupants of a building.

$\phi_{A,act}$ is the heat flow rate from appliances being used, given in W/m^2.

$\phi_{A,rest}$ is the heat flow rate from appliances that are permanently on and appliances on standby, given in W/m^2.

$\phi_{L,act}$ is the flow rate from lighting, given in W/m^2.

The previous three equations are proposed by the author as an alternative to the use of standard values for including the stochastic occupancy patterns of people in the buildings. The states active and sleep are taken from the adapted stochastic occupancy model, which is presented in section 3.2.2, and the heat flows are average typical values obtained from different standards, specified in section 3.2.5.

The following three equations correspond to the division of the solar and internal heat gains in the values that affect the temperature nodes θ_{air}, θ_s and θ_m.

$$\phi_{ia} = 0{,}5\ \phi_{int} \quad [W] \tag{19}$$

$$\phi_m = \frac{A_m}{A_{at}A_f}(0{,}5\ \phi_{int} + \phi_{sol}) \quad [W] \tag{20}$$

$$\phi_{st} = \left(1 - \frac{A_m}{A_{at}A_f} - \frac{H_{tr,w}}{9{,}1\ A_{at}A_f}\right)(0{,}5\ \phi_{int} + \phi_{sol}) \quad [W] \tag{21}$$

Where:

A_m is the effective mass area, in m^2

A_{at} is the dimensionless ratio between the internal surfaces area and the floor area

A_f is the conditioned floor area, in m^2

Step 7: The calculation of the temperature nodes θ_m, θ_s and θ_{air}, and the definition of the node θ_e .

The temperature nodes θ_m, θ_s and θ_{air}, described in equations (26), (27), (28), should be calculated under two different conditions; the first assuming $\phi_{\mathrm{HC,nd,x}}$ to be equal to 0 to calculate the temperatures under equilibrium conditions (without SC), and the second with $\phi_{\mathrm{HC,nd,x}}$ equal to $10 * A_f$ to determine the air temperature when a heating power of 10 W/m^2 is provided. The first case is denoted as $\phi_{\mathrm{HC,nd,0}}$ and the second one as $\phi_{\mathrm{HC,nd,10}}$. The resulting temperatures are also denoted with the sub-index 0 or 10 respectively.

θ_s and θ_{air} are hourly average values, but θ_m is an instantaneous value which should be calculated at the beginning and at the end of the time step (one hour) i.e. at t and $t-1$, where $\theta_{m,t-1}$ is equal to the $\theta_{m,t}$ of the previous time step. This value should be saved for every time step. The calculation of the instantaneous value is presented in equation (22).

$$\theta_{m,t} = \frac{\left[\theta_{m,t-1}\left(\left(\frac{C_m}{3600}\right) - 0{,}5*(H_{tr,3} + H_{tr,em})\right) + \phi_{mtot}\right]}{\left(\frac{C_m}{3600}\right) + 0{,}5*(H_{tr,3} + H_{tr,em})} \quad [°C] \tag{22}$$

Where:

$$H_{tr,1} = \frac{1}{\frac{1}{H_{ve}} + \frac{1}{H_{tr,is}}} \quad [W/K] \tag{23}$$

$$H_{tr,2} = H_{tr,1} + H_{tr,w} \quad [W/K] \tag{24}$$

$$H_{tr,3} = \frac{1}{\frac{1}{H_{tr,2}} + \frac{1}{H_{tr,ms}}} \quad [W/K] \tag{25}$$

$$\theta_m = \frac{\theta_{m,t} + \theta_{m,t-1}}{2} \quad [°C] \tag{26}$$

$$\theta_s = \frac{H_{tr,ms}\theta_m + \phi_{st} + H_{tr,w}\theta_e + H_{tr,1}\left(\theta_e + \frac{\phi_{ia} + \phi_{HC,nd,x}}{H_{ve}}\right)}{H_{tr,ms} + H_{tr,w} + H_{tr,1}} \quad [°C] \tag{27}$$

$$\theta_{air} = \frac{H_{tr,is}\theta_s + H_{ve}\theta_e + \phi_{ia} + \phi_{HC,nd,x}}{H_{tr,is} + H_{ve}} \quad [°C] \tag{28}$$

For the determination of $\theta_{m,t-1}$ of the first hour of the year there is no specification in the EN ISO 13790:2008. In order to determine this value, $\theta_{m,t}$ of the last hour of the year is used and an iteration of the calculation for the whole year should be run.

θ_e is the ambient temperature, and for simplification, it is also assumed to be the temperature of the air entering the building when ventilating. This simplification is part of the set of alternatives already considered in the EN ISO 13790:2008. This difference to the standard SHCP is also represented in Fig. 3 and should not generate any difference in the results since it is assumed that the buildings to be modeled do not posses any ventilation systems, which could modify the input air temperature.

Step 8: Calculation of the required power for heating or cooling $\phi_{HC,nd}$

$\phi_{HC,nd}$ should be calculated for every hour under one of three different situations. The first possible situation is one in which no heating or cooling is required, because $\theta_{air,0}$ lies between the heating set point $\theta_{int,H,set}$ and the cooling set point $\theta_{int,C,set}$.

In the second situation $\theta_{air,0}$ lies under $\theta_{int,H,set}$, which implies that energy for heating is required and $\phi_{HC,nd}$ should be calculated as defined in equation (29).

$$\phi_{HC,nd} = \frac{\phi_{HC,nd,10}(\theta_{int,H,set} - \theta_{air,0})}{\theta_{air,10} - \theta_{air,0}} \quad [W] \tag{29}$$

In the third situation $\theta_{air,0}$ lies above $\theta_{int,C,set}$, which means that energy for cooling is required and $\phi_{HC,nd}$ should be calculated as defined in equation (30).

$$\phi_{HC,nd} = \frac{\phi_{HC,nd,10}(\theta_{int,C,set} - \theta_{air,0})}{\theta_{air,10} - \theta_{air,0}} \ [W] \quad (30)$$

This calculation could be expanded to determine the actual internal temperature of the building when considering that the system has a maximum heating or cooling power, as is shown in the EN ISO 13790:2008. Due to the restriction of this customized version to only calculating energy need, no information is collected or assumed about the type of heating or cooling system used. Therefore the required power that should be provided to achieve the temperature set point is the absolute value of the result obtained from equations 29 or 30, and the number of hours where the room temperature remains uncomfortably low or uncomfortably high cannot be calculated.

To obtain the energy need for SC in a certain hour, the absolute value of $\phi_{\mathrm{HC,nd}}$ should be multiplied with the length of the time step (31).

$$E_{SC+DHW} = |\phi_{HC,nd}| * \frac{1h}{1000} \ [KWh] \quad (31)$$

3.1.3. Calculation for determining the hourly energy need for hot-water heating

The energy need for domestic hot-water heating depends on many factors. In this case, the physical characteristics of the building are not relevant. If the objective were to obtain energy demand, then the type of system and its efficiency would be required. But when considering only energy need, the relevant factors are related to the type and size of the household, as well as behavioral factors such as the volume of hot water required per person and the required water temperature (Yao and Steemers, 2005). Additionally, considering the temporal definition of the proposed method, the time when the water is required is a decisive factor.

Most of the sources that could be found to predict hot water requirements are related to standardized annual or daily values per person, or per unit area. The most detailed approach that could be found is the one implemented by the VDI (2008) to produce hot water demand profiles (together with electricity and energy demand for heating profiles) of single family houses in a one minute time step basis, and of multifamily houses in a 15 minute time step basis. This approach is based on actual demand data and an intensive measuring process of some sample houses. The results are demand distribution tables that contain values for every time step, which should be multiplied with the total energy consumption for hot-water heating to obtain a prediction of the consumption for a certain specific period of time. Lamentably, this method generates the same profile for the same type of houses, which can lead to a misrepresentation of the differences between households.

Unfortunately, many less publications could be found which try to cope with the temporal distribution of the energy need for DHW in a general approach that could generate a prediction with reduced input data. The development of an own proved approach would require obtaining very detailed information from a representative amount of households, the procurement of which exceeds the resources available for this thesis. Nevertheless, to be able to also introduce a temporal distribution of the energy need for DHW, a simple calculation procedure is proposed.

According to the proposal of Yao and Steemers (2005), the calculation procedure consists of a basic thermodynamic equation (see equation (32)) to obtain the energy required to increment the temperature of a certain volume of water from a certain input temperature to a certain output temperature. The input and output temperatures, as well as the volume of water required per person per day, are based on standard values. The temporal distribution of the consumption is determined through an occupants´ activity factor, obtained by dividing the amount of active occupants in an hour through the sum of active occupants per hour in a day.

$$E_{DHW} = \frac{C_p * \rho * V * F_{act} * (T_{out} - T_{in})}{3600} \quad [KWh] \tag{32}$$

Where:

E_{DHW} is the energy need for heat-water heating in a certain hour, given in KWh

C_p is the specific heat capacity of the water, given in $kJ/kg\ K$

ρ is the density of water, given in kg/m^3

V is the daily volume of hot water consumed by a person, given in m^3/day

F_{act} is the dimensionless occupants´ activity factor defined in equation (33)

T_{out} is the average water output temperature required for the different uses, given in $°C$

T_{in} is the water input temperature, given in $°C$

$$F_{act} = n_{O,act} / \sum_{d=1}^{24} n_{O,act,d} \tag{33}$$

Where:

$n_{O,act}$ is the amount of active occupants in the building during the actual calculation hour

$n_{O,act,d}$ is the amount of active occupants in the building in one of the hours of a given day

This approach generates a profile which follows three simple rules. First, only active occupants require hot-water. Second, the whole standard volume of hot water for a day will be consumed during the hours of activity. And third, the more occupants are active in a certain hour, the more energy is needed for DHW. Although, these rules are not necessarily always the case; for example, a washing machine could be on and requiring hot-water while occupants are sleeping or at work, or a whole family could be at home and be active for hours without using any hot-water. Additionally, a validation of the selected calculation approach of energy for DHW is unfortunately beyond the scope of this thesis. These two rules represent energy need peaks that are usually expected, such as the high requirement for hot-water for showers in the early hours of the morning when people are getting ready to go to work.

3.1.4. Total energy need for SC and DHW of a domestic building

The total energy need for SC and DHW of a building in a certain hour is the sum of the energy need for SC and for DHW (see equation (34)). Daily, weekly, monthly or yearly values could also be obtained by summing the single hourly values.

$$E_{SC+DHW} = E_{SC} + E_{DHW} \ [KWh] \tag{34}$$

3.2. Input Data

Several strategies and indirect data sources are required in order to constrain the number of input variables that should be collected from the objects of a building stock for implementing the calculation procedure. Firstly, the fundamental strategy to reduce input requirements is the use of a building typology. Consequently, a procedure for classifying the objects of a building stock using the respective types is proposed. Secondly, an occupancy pattern generator is used to determine when occupants are active, sleeping or absent. Thirdly, a procedure for determining the areas for the buildings components is applied. Fourthly, the Test Reference Years (TRY) are adopted as a fast alternative for representing the climatic conditions to which a certain building stock is typically subjected. Fifthly, further basic assumptions are made, and parameters are taken from the EN ISO 13790:2008, supplementary norms and related scientific publications.

Using these data sources allows the successful collection of the input data required to effectively run the calculation procedure for every building in a building stock by merely relying on the living area, the number of storeys, the neighboring situation, the number of occupants, the number of flats and the construction year of the building.

3.2.1. Typologies

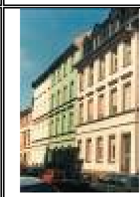
The key strategy for having simplified input when predicting the energy demand of a stock of domestic buildings is to have default data for house geometry, thermal and equipment characteristics based on vintage, and type and geographic location (in terms of countries or regions)(Parekh and Eng, 2005). This strategy has been demonstrated to be reliable and quick (Loga *et al.*, 2012, 2010; Parekh and Eng, 2005; Born *et al.*, 2003), and has been widely used in studies for energy evaluation of houses. This approach is known in the literature as the use of building typologies or building archetypes.

There is no standard formula for the development of typologies, and the methods for establishing typologies can differ widely from country to country (Loga *et al.*, 2010). However, in general the practice consists of using statistical data that is representative of the building stock of a region or a country and the separation of the building stock into groups of buildings that share similarities such as the thermal characteristics of the components of the building envelope (for example, U-Values and g-values), the area, the volume, the number of storeys, the proximity to other buildings and the construction year. Every single one of these groups is then summarized as an average or model building configuration that serves to represent of all the buildings belonging to the group. This set of average buildings then constitutes the regional or national buildings typology.

Typologies are usually used for scenario development and analysis. A common case found in the literature is the calculation of energy saving potentials when applying a certain set of refurbishment measures to the existent building stock. The energy demand of typologies is calculated under current and hypothetical conditions and characteristics. Due to the representativeness of the typologies, the results are subsequently extended to the whole building stock.

In the German case, national domestic building typologies have been developed and updated since 1990 (Loga *et al.*, 2011). Over the years, not only the number of buildings comprising the national typologies has been expanded, but also typologies have been developed for individual regions and cities (Loga *et al.*, 2011). The most current version of national typologies can be found as part of the TABULA project. This is a project where the German institute for housing and environment (Institut Wohnen und Umwelt or IWU), in collaboration with institutions of other 12 other European countries have initiated the titanic task of developing a common framework for building typologies. Most of the results and publications are already available and form a significant source of reliable information about the characteristics of the building stock of the participant countries.

The German building stock can be divided into 36 basic types and 8 sub-types. They are differentiated by geometric characteristics and neighboring situation into Single-Family Houses (SFH), Terraced Houses (TH), Multi-Family Houses (MFH), Apartment Blocks (AB) and Tower Buildings (HH). Additionally, they are grouped by vintage into ten different ranges or construction year classes that correspond to periods where the buildings were constructed with similar materials and characteristics, and to the entry in force of new thermal quality regulations for buildings. A letter between "A" and "J" is assigned to every year class, where an "A" corresponds to the oldest buildings and "J" to buildings recently constructed. The explicit division between year classes and an overview of the German typologies, including a photo of example buildings for every basic type are presented in Table 1.

Construction year class	Single-family house (SFH)	Terraced house (TH)	Multi-family house (MFH)	Apartment Block (AB)	Tower blocks(HH)
A … 1859					
B 1860-1918					
C 1919-1948					
D 1949-1957					
E 1958-1968					

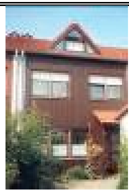
F 1969-1978					
G 1979-1983					
H 1984-1994					
I 1995-2001					
J 2002 …					

Table 1. Classification scheme of the German building typology (Born et al., 2003).

The thermal and geometric characteristics of the envelope components of these model buildings are a significant data source for the proposed method. The U-values and g-values of walls, roofs, floors, windows and doors, as well as thermal bridging and air infiltration factors are used as input data for the customized SHCP. Additional information concerning characteristics such as possessing a dormer, a heated basement or a heated attic are used as input data for the procedure for estimating the areas of the components of the building´s envelopes that is presented in section 3.2.3. All data is freely available from the web page, and documentation of the TABULA project and the specific data to be used is also recorded in Loga *et al.* (2011).

Due to the fact that the proposed method concerns only energy need (and not the end or primary energy requirements) the information about typical appliances of the different building types is not considered. Nevertheless, when customizing the SHCP attention was paid to maintain compatibility with the adapted seasonal method also consigned in the EN ISO 13790:2008 used in the TABULA project. This compatibility would allow the use of the energy effort factors calculated for the different appliances and energy sources that were calculated in the TABULA project for every building type[13], so as to obtain a quick prediction of the end and primary energy requirements for heating of the modeled buildings.

Using the national German typologies for predicting energy demand of the building stock on the sub-national level is not a new idea, and is even noted in documents such as in the guidelines for preparation of energy use plans for cities and municipalities of different German state governments. However, the suggestion is to use the energy demand values per square meter which correspond to a typology and then to multiply them by the respective area of the buildings in the regional building stock (StMUG *et al.*, 2011). The idea is certainly quick, but the process of assigning a typology for every building in the stock model is either too expensive or simply not possible using automatic procedures due to similarities between the typologies. Examples of this problem were found in Neidhart and Sester (2006) and Schüssler (2010). The solution in both cases was to create own regionalized typologies and to use alternative methods for predicting the energy demand, which unfortunately are not well documented.

Having an own calculation procedure solves the problem for the most part, because the calculation could be adapted to the geometry of every building in the stock, and if the building envelopes posses similar characteristics the classification of a building into one of two or several typologies could be radically simplified or even avoided.

Using the typical values for number of storeys, conditioned area, and a geo-analysis procedure for identifying neighboring buildings and the construction year class, a simple and easily implementable decision algorithm has been developed for the classification of the objects of a building stock into the German typologies.

The first criterion for classifying a building into a typology is the construction year. Using the same ranges of the TABULA typologies, a building could be placed into one of ten different groups (see [a] in Fig. 4). A more complicated task is to determine to which of the construction types a building does belong. To achieve that, several decision criteria should be added.

Using the number of storeys as criterion, it is possible to divide the typologies into two raw groups: One group with less than three storeys including the SFHs and the THs, and other with three or more, which includes the MFHs, the ABs and the HHs. This criterion probably generates an incorrect prediction for the last three construction year classes of the TH because this group could also typically contain objects with three storeys. However, this problem could be solved if buildings of

[13] See Loga *et al.* (2011)

these construction year classes and with three storeys are also differentiated by the reference area which is noticeably larger in the case of the MFH (an arbitrary boundary value of 200 m^2 has been selected). After that, there are six typologies which can be completely identified, SFH_A, MFH_A, MFH_G, MFH_H, MFH_I, and MFH_J (see [b] in Fig. 4).

Subsequently, SFHs and THs could be differentiated through the number of neighboring buildings. It is expected that terraced houses have at least one neighboring house, but it is also possible that a SFH (specially following the model houses of categories G and H) has a neighboring house (semi-detached houses) and therefore a differentiation criterion based on one neighboring house would not be enough. However, THs are also expected to constitute groups where two houses have one neighbour (the houses on the corners) and at least one house possessing two neighbors (a house in the middle of two corner houses). Identifying these groups of houses will allow us to recognize which of the buildings are THs.

To identify these groups automatically, a geo-neighbour-analysis could be performed. The minimum requirement for doing that is a geo-referenced map where the buildings of the building stock are represented as individual objects, and software capable for geo-analysis. When using ArcMap the task could be carried out by using the following procedure:

a. Using the "near" tool and selecting the objects with a distance equal to 0 allows the identification of all buildings which have at least one neighbour.

b. The selected objects are used to generate new objects by using the "cartography tool" named "polygon aggregation".

c. At the same time, a "near table" should be generated for the whole building stock, and the events contained in this table should be displayed in a layer by using the coordinates. A new layer should be generated with objects having a distance to others equal to 0.

d. A "spatial join" between the objects obtained from the "polygon aggregation" and the displayed events of the "near table" generates a new layer with objects (polygons) containing one or more event (point). Objects containing two or more points are groups of buildings meeting the conditions to be THs. These groups can be automatically identified by selecting the objects placed in the attribute table in the field "join count", which are higher than two.

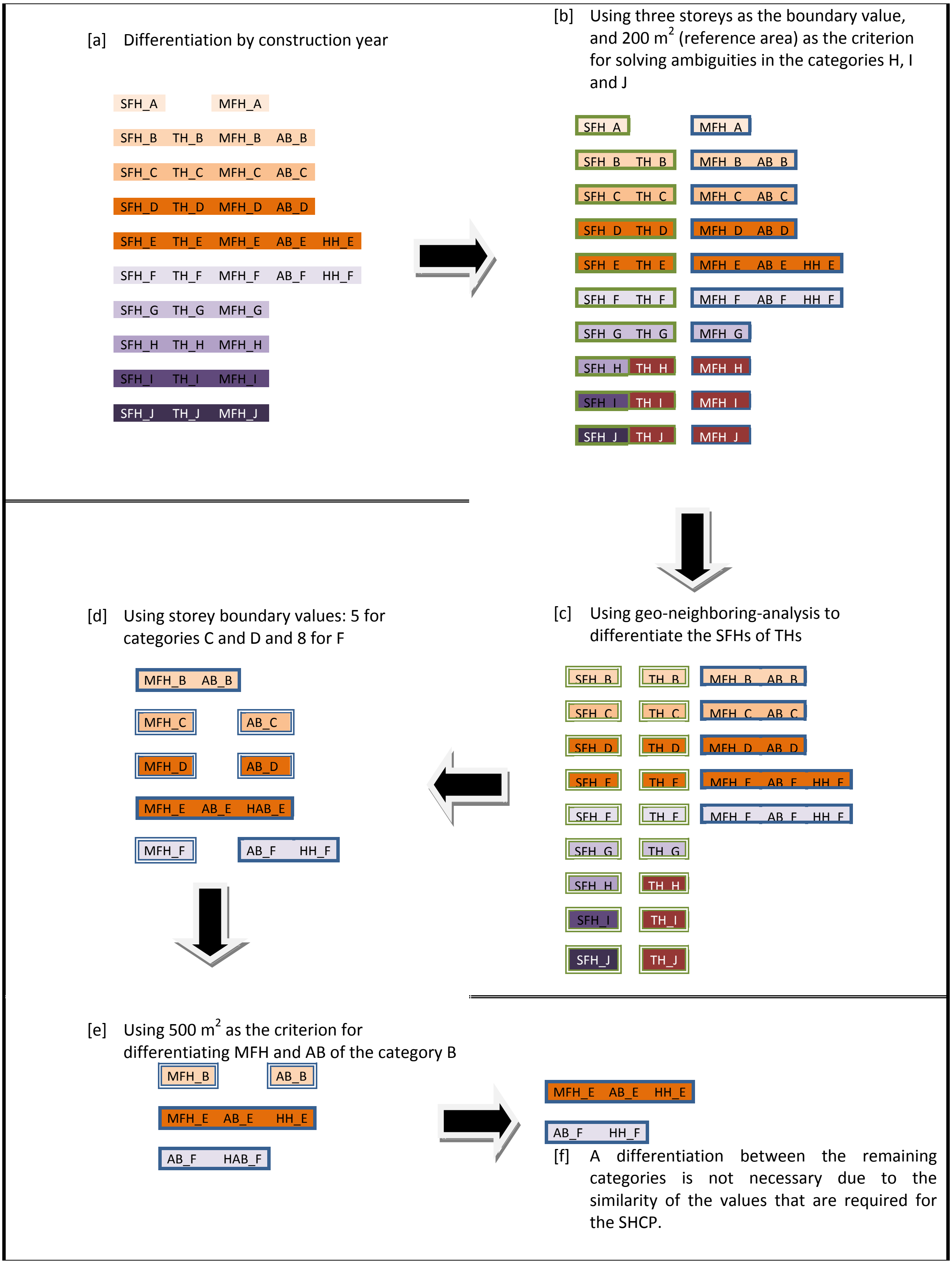


Fig. 4. Graphical summary of the decision algorithm for classifying the objects of a building stock into the German typologies.

For the remaining building types a second classification based on the number of storeys could be performed. For the construction year categories C and D, a 5 storeys boundary value can be used; I.e. buildings in these categories with less than 5 storeys are MFH, and with 5 or more are AB. For the category F, an 8 storey house boundary value also works to differentiate the MFHs of the ABs (see [d] in Fig. 4).

The differentiation between the buildings of the type MFH_B and AB_B should be made based on the reference area, which is noticeably larger in the case of the AB_B. For doing that in this case, an arbitrary boundary value of 500 m^2 has been selected (see [e] in Fig. 4).

There are no geometric characteristics which allow for the differentiation of the remaining building types in the categories E and F (see [f] in Fig. 4). However, the values that should be obtained from the typologies for calculating the energy need are the same for these remaining typologies. And, the input data that make the difference in the calculation of the energy need are Area and Number of Storeys, which in any case are collected data.

3.2.2. Active occupancy patterns

Occupant presence and behavior have a very large effect on the energy performance of buildings (Andersen, 2009; Haas *et al.*, 1998; Haldi and Robinson, 2010; Kiesel *et al.*, 2010; Maier *et al.*, 2009; Mullaly, 1998; Page, 2007; Page *et al.*, 2008; Papakostas and Sotiropoulos, 1997; Parys *et al.*, 2010; Reinhart, 2004; Robinson *et al.*, 2011; Yu *et al.*, 2011; Shimoda *et al.*, 2004). Following the classification proposed by Page (2007), the different means of impact of occupants in the energy requirements of a building are:

- Production of internal metabolic heat gains.
- Selection and control of the set-point for heating and cooling.
- Position of blinds that influence radiation transmission and glass surface temperature.
- Use of artificial lighting, which results in internal heat gains and electricity consumption.
- Use of windows and doors, which also results in heat gains and losses through ventilation.
- Use of appliances, which affect electricity and hot/cold water consumption as well as internal heat gains.

The SHCP includes variables for representing every single one of these means of impact, and the literature offers a variety of options for their representation or simulation. However, most of the models that simulate the interaction of occupants with appliances, windows and doors, lighting systems and blinds were developed and tested for office buildings. Additionally, to avoid over-complicating the proposed method, the customized SHCP includes only deterministic rules and typical values for the input variables concerning the occupant´s means of impact. These variables and rules are presented in section 3.2.5.

Nevertheless, the occupant´s means of impact all have a common denominator; they vary considerably in respect of time. This variation is mostly correlated to the occupancy pattern of the building residents, where in the domestic sector, the periods when people are at home and active play a primary role (Paauw *et al.*, 2009; Richardson *et al.*, 2008; Robinson *et al.*, 2009; Yao and Steemers, 2005). The representation of the variation over time in the energy need for SC and DHW is one of the main objects of the proposed method, and therefore the customized SHCP make special emphasis on this point.

The occupancy patterns are commonly represented with fixed schedules, and the differences between buildings are illustrated with so-called "diversity profiles". The fixed schedules are usually based on typical values extracted from data collected from an extensive amount of buildings, from national guidelines or even simply deducted using common sense (Page, 2007). The "diversity profiles" are usually constructed depending on the use of the building (residential, commercial, educational facility, etc.) or occasionally on the type of occupants (e.g. income or size and composition of the household) (Ibid). Unfortunately, the use of fixed values misrepresents the randomness that is intrinsic to the occupancy patterns of buildings.

The use of stochastic models for generating synthetic occupancy patterns that are able to show the randomness of residents' behavior has been subject to several publications in recent years. In order to obtain the necessary input data for the customized SHCP, two different alternatives for stochastic occupancy patterns have been examined. The alternatives have been selected due to their resonance in further publications, where these models were used as the basis for modeling the energetic behavior of buildings.

The first alternative, proposed by Page (2007), is a very ambitious model which aims at generating time series of states of presence (absent or present) for each occupant of a zone, and for each zone of any number of buildings. This model represents not only times of arrival and departure, but periods of intermediate and long absence from the considered zone. The model was tested on occupancy data from private offices, but the authors affirm that the model is usable in all types of buildings. In fact, the model was designed to be included in the so-called software SUNtool and in its successor called CitySim which should be able to model the energy flows of entire neighborhoods and cities to support sustainable urban planning.

The major shortcoming of the proposal of Page *et al.* (2008) is its complexity, which was recognized when published by its authors. In fact those explicitly mentioned wanted to continue working on alternatives in order to simplify the model. Unfortunately, no further publication concerning the simplified model and none of the software packages could be found. Moreover, Robinson *et al.* (2007) used SUNtool to simulate the Olympic village of Athens, but they disengaged the stochastic models “for simplicity”. Likewise, Robinson *et al.* (2009) explicitly said that the stochastic occupancy model is integrated with CitySim but is “currently disabled”, and what´s more, they manifested their intentions to replace the model. Overall, its complexity and unavailability calls for this model to be disguarded.

The second alternative is proposed by Richardson *et al.* (2008). They developed a stochastic model for generating synthetic occupancy data on a ten minute time-step basis, for a weekday or a weekend day, and for households with up to six members. The occupancy patterns consist of 144 “states” which correspond to the periods of ten minutes that are contained in a day. These states are integer numbers that represent the number of active (at home and not asleep) occupants in a household.

The model relies on a first order Markov-chain technique for determining the states. This technique has the advantages of being widely used and simple to implement (Gamerman, 1997; Gilks *et al.*, 1996). The basic idea behind this technique is that each state depends only on the previous state and the probability of that state changing. The key component when applying the technique is the definition of the probabilities of every state, which are held in the so-called “transition probability matrices” (Ibid). For the construction of the matrices Richardson *et al.* (2008) used the Time-Use Survey (TUS) data from the year 2000 in the UK. Surveys like this were designed to measure the amount of time that the population spends on their daily activities. The data sets include 9000 24-hour diaries in a ten minute resolution, and the active category was derived from time periods when the persons declared themselves to be at home and not asleep.

The resulting model is able to generate occupancy patterns, which possess similar characteristics to the ones contained in the TUS. The authors compared the data of the survey with the simulation of 10.000 houses for every household size, and obtained a close correlation in all cases. Additionally, the model has also proved to be computationally very efficient, i.e. it is able to generate large quantities of data very quickly (Richardson *et al.*, 2008). A detailed example of the model was made freely available by the authors. They recorded all required data in a Microsoft excel workbook and implemented the algorithm using Visual Basic. They also declared the code open and made it accessible at http://hdl.handle.net/2134/3112 (Ibid).

The model has served as the basis for several further models concerning the energy requirements of domestic buildings in different countries around Europe. Cheng and Steemers (2011) use the results of the model together with the model of Yao and Steemers (2005), to determine heating patterns of domestic buildings in the UK. Paauw *et al.* (2009) make use of the algorithm together with the TUS of the Netherlands for generating occupancy patterns that included active and sleeping occupancy for 15 minute periods and then used these patterns as the basis for an energy pattern generator for five different household types, concerning electricity and heat demand. Andersen (2009) modified the excel Workbook for generating yearly time series and used it as the basis for investigating the consequences of occupants behaviour on the energy performance of Danish dwellings. Finally, Richardson *et al.* (2010) made use of the model as the core for the domestic electricity use model, which is presented in chapter two of this thesis.

Similarly to Andersen (2009), the customized SHCP $n_{O,act}$ (amount of active occupants in the building during a certain calculation hour) and $n_{O,sle}$ (amount of sleeping occupants in the building during the actual calculation hour) are to be determined from a modified version of the Excel workbook document made available by Richardson *et al.* (2008). This modified version includes the following changes:

a) The source code is modified to generate yearly time series, in which every day is a new simulation, and differences between weekdays and weekends are taken into account. These time series begin on the Monday of the first week and ended on Monday of the fifty-third week.

b) For obtaining hourly time-steps, the states of the ten-minute time-steps of every hour are summed together and divided by the amount of ten-minute time-steps that are contained in an hour (i.e. 6). This change generates hourly states that are no longer only an integer, but could also contain decimal components which represent how many persons were active during a number of ten-minute time-steps during an hour. For example, if in a household of two persons, every person is active during three ten minute time steps in a certain hour, the state of this hour is equal to 1; In the case that just one of the two household members is active for three ten-minute time-steps, the state is equal to 0,5; Finally, if both persons are active during the 6 ten-minute time steps of an hour, the state is naturally 2.

c) A second time series is generated for determining $n_{O,sle}$ based on typical values and the hourly active state obtained previously. The sleeping states correspond to members of the household who are inactive in the period between 23:00 and 07:00 of the next day. This second time-series is necessary to reduce the internal metabolic heat gains, which are considerably lower when humans are sleeping, and to set a basis for a rule concerning the night set-backs that are explained in section 3.2.5.

d) The source code was also adapted to be used with building stocks where the buildings contain more than one household. This means that the adapted workbook is able to automatically generate occupancy patterns for almost every possible number of occupants of a building, except in the case when households of more than 6 persons are to be modeled. However, due to the fact that the SHCP considers every building, independent of the number of households as just one zone, it should be possible to model the additional persons separately. The hourly states of a building are therefore the sum of the states of the households.

The use of this stochastic occupancy pattern generator represents important advantages over the use of fixed schedules and diversity patterns. However, there are also shortcomings with this particular model that must be kept in mind:

- The generated time series do not take into account patterns of consistency between days. This means that all the weekdays of a household in a year could be different, and that households that have an occupancy schedule which is very similar from day-to-day is only simulated coincidentally.

- Also the independency of every simulated day neglects the possibility of considering large periods of absence of the buildings´ occupants, and therefore events such as holidays cannot be considered.

- The time series with sleeping states is based on the assumption that all household members at home are either active or sleeping between 23:00 and 07:00 the next day, every day, and therefore the possibility of considering that persons perform any type of activity outside the building at night is neglected.

- For the first approximation and for the early planning stage, the model runs under its original assumptions (i.e. without adapting it to the respective national TUS), which should serve the purpose of enriching the model for the respective district or municipality with diversity in the occupancy patterns of the modeled buildings. However, depending on the objectives and the level of detail required, not just the use of the national TUS should be necessary but also a classification based, for example, on socio-economic characteristics could be desirable.

3.2.3. Areas

The areas of the conditioned space and several different components of the building´s envelope are required to complete the calculation procedure. There are two different reference areas which are commonly used in the German case as conditioned areas. The first one is proposed in the "Energieeinsparungsverordnung" (energy saving regulation), better known as EnEV, which is similar to the net internal area of the building (total building area measured inside external walls). It can be calculated by multiplying the volume of the building from external measures with 0,32 (Bundesregierung Deutschland, 2009). The second is the conditioned living area defined as the section of the conditioned net floor area inside of the apartments of a building, which is a key measure for construction permits, market transactions (renting, selling) and national statistics.

The comparison of actual energy consumption of domestic buildings against predictions made with both options for reference area has shown that using the conditioned living area leads to more accurate results (Loga *et al.*, 2011). For this reason the preferred reference area for the customized SHCP is the conditioned living area.

In the German case, most of the accessible geo-referenced data includes only the area of the buildings measured from the outside (conditioned gross floor area). To gain the conditioned living area per storey, the conditioned gross floor area should be multiplied by the factor 0,772. This factor is derived from the conversion factors for typical reference areas used in the European context to a common reference area (the net internal area of the building) published in Loga *et al.* (2009). The net internal area of the building can be obtained by multiplying the conditioned gross floor area by 0,85, with the net internal area being 1,1 times the conditioned living area. The total conditioned living area is assumed to be the result of the multiplication of the conditioned living area per storey by the number of storeys.

Conventionally, when using a building physics based approach the areas of the building´s envelope components are calculated as fixed percentages of the conditioned areas, which are derived from the model buildings of every type. Despite the fact that such an approach seems to be valid when no further information is available, its accuracy is normally not tested or even discussed.

In the German case, a statistically tested procedure could be found. Aimed at coping with the problem of a very demanding measuring process when performing energy consulting for domestic buildings, Loga *et al.* (2005) developed a procedure to determine the areas of building´s envelope components by relying solely on the conditioned living area, number of full storeys, neighboring situation of the building, room height, design type (compact or stretched), partial heating degree of attic and basement as well as the characteristic of buildings having a dormer or not. This procedure was developed by performing a statistical analysis of a sample of 4.000 buildings, which were deemed to be representative of the German building stock. As a demonstrative example of the procedure, the authors used predicted areas to calculate the transmission losses of 38 of the German building typologies (all types and subtypes excluding the construction year category J) and compared those losses with the values obtained when using the actual areas. The results of the comparison showed a maximum variation of +23% and -20%, a mean variation of -1%, and a standard deviation of the variation of 11% (Ibid). The results from the model for predictions applied to non-typical buildings are only slightly more inaccurate. The accuracy of the procedure is a strong argument for using it as pre-procedure to gain the input data for the customized SHCP. The required input data for this pre-procedure and its sources are presented in Table 2. The procedure itself is presented in equations 35 to 43.

Symbol	Units	Explanation	Values	Source
A_f	m^2	Conditioned living area (conditioned gross floor area * 0,772)		GIS maps
n_{VG}	–	Number of full storeys		GIS maps/ local survey
n_{neigh}	–	Number of directly adjacent neighboring buildings	0 (detached), 1 (semi-detached) 2 (attached)	GIS maps
T_{GR}	–	Design type	K (compact) G (stretched)	Model buildings from the typologies (the value is always K)
$f_{TB,BA}$	%	Partially conditioned basement	0 (without basement) 0(unconditioned basement) 50 (partially conditioned basement) 100 (fully heated basement)	Model buildings from the typologies / survey
$f_{TB,ATT}$	%	Partially conditioned attic	0 (without attic) 0(unconditioned attic) 50 (partially conditioned attic) 100 (fully heated basement)	Model buildings from the typologies / survey

f_{DO}	–	Correction factor for dormers and other roof construction	1,0 (without dormer) 1,3 (with dormer)	Model buildings from the Typologies / survey
he_{room}	m	Room height		Survey / GIS /Standard value (2,5 m)
p_{Da}		Roof area per m^2 floor living area	1,33 (flat roof) 0 (unheated) 1,5 (fully heated)	Parameters in Loga *et al.* (2005)
p_{OG}		Area of uppermost storey ceiling	0 (flat roof) 1,33 (unheated) 0 (fully heated)	Parameters in Loga *et al.* (2005)
p_{Fa}	–	Façade area for each full storey per m^2 floor living area	0,66	Parameter in Loga *et al.* (2005)
q_{Fa}	m^2	Façade surcharge area per full storey	50 (detached), 30 (semi-detached) 10 (attached)	Parameters in Loga *et al.* (2005)
p_{Fe}	–	Window area per m^2 conditioned living area	20	Parameter in Loga *et al.* (2005)
p_{FB}	–	Ground Floor area per m^2 floor living area	1,33	Parameter in Loga *et al.* (2005)

Table 2. Input data and parameters for the procedure for estimation of the areas of the building´s envelope components. Own adaptation, based on Loga et al. (2005).

Determining the number of conditioned storeys n_G:

$$n_G = f_{TB,BA} + n_{VG} + 0{,}75 * f_{TB,ATT} \quad (35)$$

Determining the conditioned living area per storey ("floor living area") $A_{W/G}$:

$$A_{f/G} = \frac{A_f}{n_G} \quad [m^2] \quad (36)$$

Estimating the ground floor area A_{FB} :

$$A_{FB} = p_{FB} * A_{f/G} \quad [m^2] \quad (37)$$

Estimating the area of the roof A_{Da} and of the uppermost storey ceiling A_{OG} :

$$A_{Da} = f_{DO} * p_{Da} * A_{f/G} \quad [m^2] \quad (38)$$

$$A_{OG} = p_{OG} * A_{f/G} \quad [m^2] \quad (39)$$

Estimating the façade area per storey A_{Fa} :

$$A_{Fa} = \frac{he_{room}}{2{,}5m} * (p_{Fa} * A_{f/G} + q_{Fa}) \quad [m^2] \quad (40)$$

Estimating the area of the windows A_{Fe}:

$$A_{Fe} = p_{Fe} * A_f \qquad [m^2] \qquad (41)$$

Estimating the area of the basement walls in contact with the ground or an unconditioned basement A_{AWK}:

$$A_{AWK} = 0{,}5 * f_{TB,BA} * A_{Fa} \qquad [m^2] \qquad (42)$$

And finally, Estimating the external walls´ area A_{AW} :

$$A_{AW} = n_G * A_{Fa} - A_{AWK} - A_{Fe} \qquad [m^2] \qquad (43)$$

3.2.4. Climate data

The customized SHCP requires hourly values for external temperature (θ_e), wind speed (v) and solar radiation for different inclinations and with a given orientation ($I_{sol,k}$) for a year. The EN ISO 13790:2008 recommends using the Test Reference Years (TRY) to gain this data. This data is especially thought to serve as input data for computer supported simulations of buildings´ energy consumption, solar energy and indoor climate control systems.

In the German case, an actualized version of the TRY was published and made freely available to the public in April 2011. The data sets are divided into 15 different German climate zones. To define every zone a cluster analysis was performed, and a representative measuring station was selected. For the generation of the data, observations and measurements from the period 1988 to 2007 together with smoothing and interpolation methods have been used (Deutscher Wetterdienst, 2011). The data sets include not just typical years, but also years which experienced extreme winters, an extreme summers, and additionally, predictions of these three weather situations in 2050 for every representative measuring station (Ibid). Furthermore, software is included to generate new data sets which take into account differences generated by the urban structure (for accounting for the heat island effect) and the height above the sea level of the studied location (Ibid).

The TRY contains all required climate input data for the SHCP, except for solar radiation on non-horizontal surfaces. In order to gain this information, the procedure described in GBG (2012) (equations 1 to 50) is to be followed. The procedure is explained in detail, mostly self-contained and when not, it relies only on the TRY. No adaptation or further consideration is made to the procedure and therefore a detailed description is not included in this thesis.

3.2.5. Further assumptions and standard parameters

Despite the fact that most of the input data required for the customized SHCP can be obtained from the four sources explained previously, further assumptions and standard parameters are necessary to avoid an increase in the amount of data to be raised.

A first group of assumptions concern solar radiation and the geometry of the buildings. The procedure described in GBG (2012) is only implemented for two different alternative inclinations, 90° and 45°. This implies that simulated buildings possess only perfectly vertical walls (90° inclination) and that there is just one type of roof (45° inclination) for buildings with non flat roofs. Moreover, it is assumed that the external walls of buildings are only to be aligned on the basic cardinal points: North, South, East and West and that they are equally distributed. These simplifications are made in order to deal with the fact that GIS information, including detailed characteristics of roofs and walls (LoD2), is still scarce. The characteristic of having a flat roof, or not, can be derived from the model buildings in the German domestic buildings´ typology, available in Loga *et al.* (2011) . Similarly, in the case that there is no further available information, the distribution of windows to the different orientations is to be derived from factors based on the model buildings of the TABULA typologies.

The second relevant group of assumptions to be made corresponds to the internal temperature set-points. The proposed model does not include integration to a statistics based bottom-up model for the determination of the internal temperature set-points according, for example, to the socio-economic characteristics of the occupants of the building. Nevertheless, it is expected that newer buildings present higher internal temperatures due to factors such as for example the rebound effect generated due to the lower cost of heating (Born *et al.*, 2003; Haas *et al.*, 1998; Schuler *et al.*, 2000). Analogously, old and badly isolated houses usually have lower internal room temperatures due to the significantly higher costs of heating (Born *et al.*, 2003; Loga *et al.*, 2003). In the German case, it has been found that actual average internal room temperatures can range between 15°C in old and large buildings, and 24°C in modern and compact buildings (Loga *et al.*, 2003; Loga, 2005). Unfortunately, a well defined function to describe this situation could not be found and therefore fixed values for the different construction year classes are used. 16° C for construction year classes A to E, 18° C for F and G, 20° C for H and I, and 23°C for J.

Internal room temperatures are also affected by night set-backs and partial room conditioning of the buildings (CEN, 2008; Loga *et al.*, 2003; Born *et al.*, 2003). The proposed method is not able to model partial room conditioning of buildings, although a rule for reflecting night set-backs is included. For buildings with just one household, the heating set-point is reduced to 15°C when all of the household members are sleeping. And for buildings with more than one household, it is enough for 50% of the occupants to be classed as asleep in order to reduce the temperature to 15°C.

Concerning the cooling set-point; not much information is available in the German case (usually not taking into account domestic buildings due to their theoretically low importance considering the national climate conditions) but for the provision of an approximation, the standard value 26°C is used as suggested in CEN (2008) and also adopted by Kämpf (2009) (who proposed and tested the calculation engine similar to the SHCP which was considered in section 3.1.1).

The third group of assumptions corresponds to input values that are used for all buildings and mostly correspond to standardized values described in the EN ISO 13790:2008 for completing the SHCP. The values, their sources and their explanation are presented in Table 3.

Finally, in order to be able to consider refurbishment measures applied to certain buildings (in the case that the information is available), the TABULA values for conventional refurbishment measures[14] applied to the buildings of the German typology are used. An exhaustive description of the applied modifications to the model buildings of the German typology and the respective u-values, g-values, etc. that are necessary for the customized SHCP can be found in Loga *et al.* (2011). These values were also checked, and they fulfill the condition required for the last step of the decision algorithm presented in Fig. 4. For this reason, no further consideration is required for modeling buildings which were the object of conventional refurbishment.

Symbol	Value/ Calculation	Unit	Explanation	Source
h_{is}	3,45	W/m^2K	heat transfer coefficient between the air node (θ_{air}) and the surface node (θ_s)	EN ISO 13790
A_{at}	4,5	-	dimensionless ratio between the internal surface area and the floor area	EN ISO 13790
$h_{tr,ms}$	9,1	W/m^2K	thermal transfer coefficient	EN ISO 13790
A_m	2,5 *A_f	m^2	effective mass area	EN ISO 13790
b_{tr}	0,5 (winter) 1,5 (summer)	–	adjustment factor used to contemplate the effect of the difference of the external temperature and the temperature of the soil in contact with the ground floor	EN ISO 13790 / TABULA
$\rho_a c_a$	0,33	$Wh\ /\ (m^3k)$	heat capacity of the air per volume	EN ISO 13790
k	165000	$J\ /\ (m^2k)$	the internal heat capacity per area of building element of the “medium” class	EN ISO 13790
$F_{sh,ob,k}$	0,80 (Horizontal) 0,60 (Vertical)	–	dimensionless shading reduction factor for external obstacles for the solar effective collecting area of surface k.	TABULA
$F_{r,k}$	1 (Horizontal) 0,5 (Vertical)	–	form factor between the building element and the sky	EN ISO 13790

[14] Equivalent to the necessary refurbishment to fulfill the requirements of the EnEv 2009

F_F	0,3	$-$	frame area fraction, ratio of the projected frame area to the overall projected area of the glazed element	TABULA
R_{se}	$1/h_c h_r$	m^2K/W	external surface heat resistance of the opaque building element	EN ISO 6946
h_r	$4\varepsilon\sigma{T_m}^3$	W/m^2K	Radiative coefficient of the surface resistance	EN ISO 6946
ε	0,9	$-$	Hemispherical emissivity of the surface	EN ISO 6946
σ	$5,67 * 10^{-8}$	W/m^2K^4	Stefan-Boltzman constant	EN ISO 6946
T_m	$\theta_e + 273,15$	K	Thermodynamic external air temperature	EN ISO 6946
$\Delta\theta_{er}$	11	K	the average difference between the thermodynamic external air temperature and the thermodynamic apparent sky temperature for intermediate zones (between sub-polar areas and tropics)	EN ISO 13790
h_c	$4 + 4v$	W/m^2K	Convective coefficient of the surface resistance	EN ISO 6946
$\alpha_{S,c}$	0,75	$-$	dimensionless absorption coefficient for solar radiation of the opaque building elements (the value is an average considering the materials present in the buildings´ typologies)	Professur für Bauphysik der ETH Bauphysik Online
$q_{ve,act}$	42 for SFH and 28 for the rest	$m^3/(h\ person)$	the airflow rate with external air per person	EN ISO 13790
$\phi_{O,act}$	125	$w/\ person$	Heat flow rate from active persons	EN ISO 7730 and DIN 33403
$\phi_{O,sle}$	70	$w/\ person$	Heat flow rate form persons sleeping	EN ISO 7730 and DIN 33403
$\phi_{A,act}$	2	W/m^2	heat flow rate from appliances being used [15]	DIN 4106-8, EN ISO 13790:2008, and Arbeitshilfe Klimakälte (DS-Plan Gmbh and Institut Wohnen und Umwelt Gmbh, n.d.)
$\phi_{A,rest}$	0,2	W/m^2	heat flow rate from appliances that are permanently on and appliances on standby [12]	
$\phi_{L,act}$	2	W/m^2	heat flow rate from lighting [12]	
V	0,04	m^3/day	daily volume of hot water consumed by a person	Yao and Steemers (2005)
T_{out}	50	$°C$	average water output temperature required for different uses	Yao and Steemers (2005)
T_{in}	10	$°C$	Average water input temperature	Din 4108-6

Table 3. Standard parameters to be used with the customized SHCP.

[15] These values cannot be found in a disaggregated form at this level of detail, and they depend strongly on factors such as appliance ownership; the prediction of which exceeds the purpose of this thesis. However, several calculation tests were performed in order to assure the plausibility of the values when comparing them with standard values and the related sources presented.

3.3. General scheme for the method

The different components of the proposed method are integrated following the scheme presented in Fig. 5. The specific data sources for a certain building stock are GIS data and local data banks. The interesting input data that should be obtained are construction year, the conditioned area of the buildings as wells as their geo-referenced position, number of storeys, number of flats and number of occupants. These data serve as the basis for the procedure to determine the areas of the building envelope components; the decision algorithm for classifying each building into a respective typology; the model for generating stochastic occupancy patterns; and for a GIS based analysis to determinine the neighboring situation for the buildings, which at the same time is required for the decision algorithm.

After classifying each building into a certain typology, the u-values, g-values and other typical required input data from the typologies can be incorporated into the customized SHCP. In the case that it becomes known that the building has been refurbished, the necessary data can be replaced by data corresponding to the results for typical refurbishment measures.

The data from the occupancy pattern generator and the areas of the envelope components of each building should also be integrated into the customized SHCP.

The following step is the incorporation of the climate data: Ambient temperature and wind speed are directly extracted from the TRY depending on the geographic area where the district or municipality is located. Solar radiation should be pre-processed following the method recorded in the GBG (2012).

The areas of the envelope components for each building together with the rest of the required information that is recorded in standard and further publications should also be incorporated into the customized SHCP.

At the same time, the occupancy patters and standard amount of warm water are integrated into the calculation to determine the hourly energy need for DHW.

The customized SHCP and calculation for DHW should be run for each building in the stock. The individual results are put together by using GIS tools, and the final result of the method is a spatial and temporal model for the energy need of SC and DHW from the studied district or municipality.

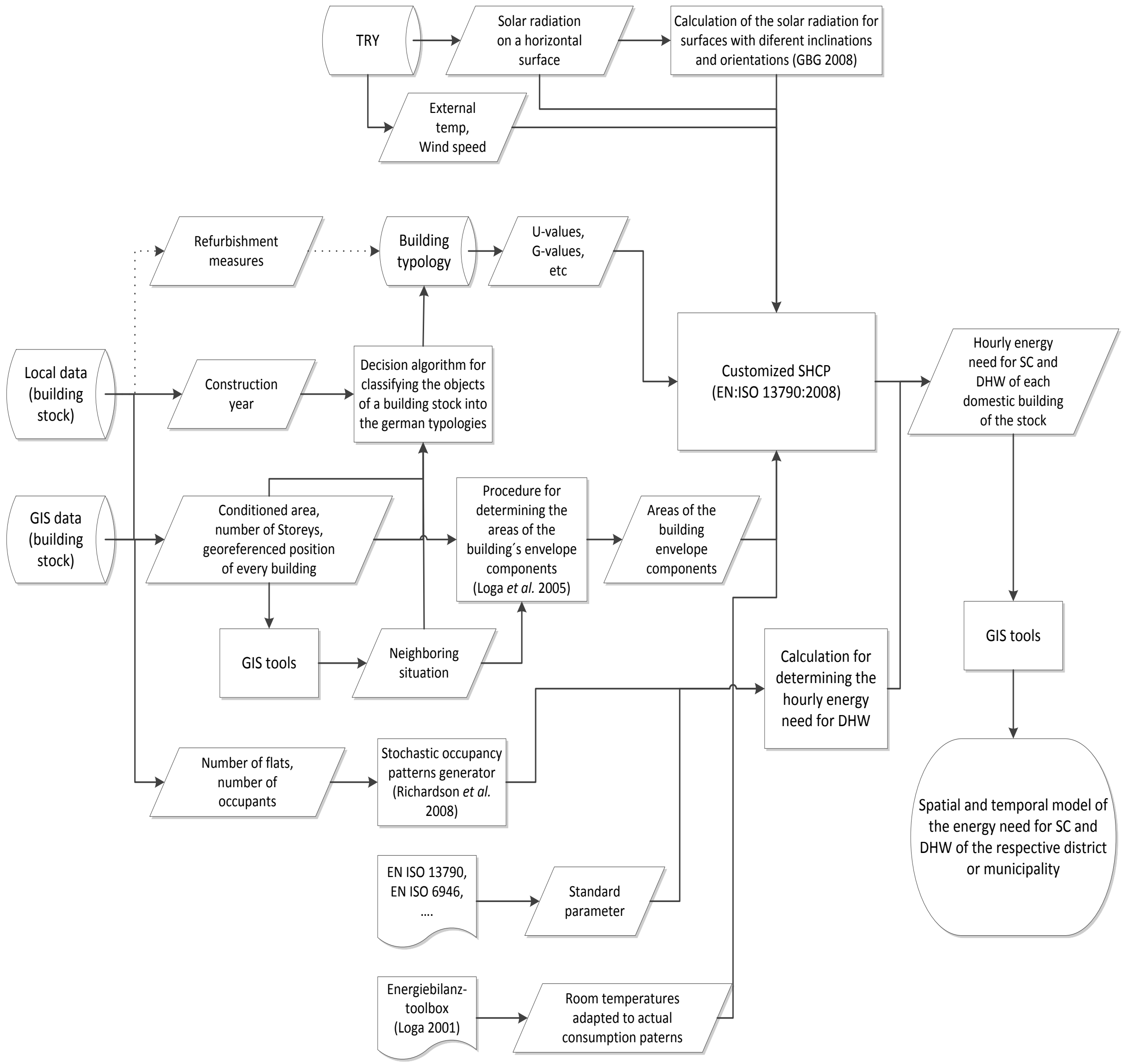


Fig. 5. Depiction of the proposed method for predicting hourly domestic energy need for space conditioning and water heating of districts and municipalities.

4. Testing the Method

Models and model based analysis are usually evaluated and criticized for the plausibility of their assumptions and results, and for their ability to effectively represent the events or phenomena for which they were designed for. In the scientific community this concern is identified as the problem of the GIGO (garbage in, garbage out) models (Saltelli, 2002). One of the most common facets of this problem occurs when complex models with a large number of assumptions, parameters and state variables are tuned, and their input variables are arbitrarily restricted to improve the precision of outputs (Ibid).

In the field of bottom-up models for predicting energy consumption of domestic buildings, the lack of quantification of uncertainties concerning input data, assumptions and results is also a significant source of criticism (Kavgic *et al.*, 2010). In fact, just one of the five relevant models for the UK reviewed by Kavgic *et al.* (2010), the CDEM, was tested for uncertainties. In this case Firth *et al.* (2010) used a local sensitivity analysis to examine the effects that changes in the magnitude of input variables have on the results from their model. Further use of such a technique for UK models could be found solely in the model of Cheng and Steemers (2011), who performed the same type of local sensitivity analysis as Firth *et al.* (2010), thus allowing an inter-model comparison.

The situation does not improve in the international context. None of the further international models reviewed by Kavgic *et al.* (2010) include an evaluation of uncertainties, and none of the models for European countries reviewed for chapter two of this thesis make use of a formal approach for testing uncertainty. In most of the publications, the uncertainties related to the models are mentioned but not quantitatively evaluated.

Problems with models are not only restricted to their inherent uncertainty. “More manageable” problems such as lack of transparency and mistakes when constructing and implementing the models are also a source of criticism. This lack of transparency affects the credibility of models and hinders the possibility for replication. Nevertheless, despite the fact that this issue could be solved (theoretically) without a great deal of effort, society has been dealing with it (not just in the case of modeling) for a long time and no definitive solution has yet been found.

Concerning the development and implementation of models, the situation is more promising. In the case of building energy and environmental modeling, significant effort was invested during the 1980s and 1990s with the aim to develop techniques for verification and validation (Kämpf, 2009). Verification includes checking that the computer code (program) does what the algorithm is designed to do, correcting possible mis-conceptualizations or typing mistakes that have occurred during the implementation (Wainwright and Mulligan, 2004; Fishman and Kiviat, 1968). Furthermore, validation concerns the testing of the model outputs to determine whether the model is an accurate representation of the real world system under study or not (Fishman and Kiviat, 1968). Typical techniques for verification and validation include code checking, inter-model comparisons and empirical comparisons (Kämpf, 2009).

The proposed method possesses six individual components which should be subject of verification and validation:

I. The calculation of solar radiation for surfaces with different inclinations and orientations.
II. The procedure to determine the areas of buildings´ envelope components.
III. The stochastic occupancy patterns generator.
IV. The calculation to determine the energy need for DHW.
V. The customized SHCP.
VI. The decision algorithm used to classify the objects of a building stock to match the German typologies.

In cases I to V, the validation process for the basic algorithms was already performed in the original publications. Especially the SHCP, the core part in the method, has been object of further independent validation through inter-model comparisons (see section 3.1.1). Additionally, special attention has been paid when customizing it to remain within boundaries specified in the EN ISO 13790:2008 (see section 3.1.2). Thus, no supplementary validation of these method´s components was performed.

It would be interesting to test the results of the interactions between III and IV, and between III and V. However, an empirical comparison would be restricted by the number of cases for which high quality data sets exist (in the case that they exist, and to keep in mind that they are also subject to measurement uncertainties), and an inter-model comparison for testing hour to hour results would not make sense since most of the detailed procedures (such as RT methods or CTF methods used usually for exhaustive simulations and included in popular software packages) make use of fixed schedules. Moreover, the objective of this thesis, as well as the original occupancy pattern generator, is to show the variability that could take place in the schedules of households: and this characteristic was already tested by the developer of the stochastic occupancy model.

However, the ability of the method to deliver plausible and robust results as well as the capacity of VI to generate accurate classifications should be validated. Two different approaches are used. Firstly, the proposed method is used to model the buildings in the German typology, and its results are compared to yearly typical values adapted to actual consumption. Moreover, the effect of uncertainty concerning the primary input data on the set of model buildings from the German typology is tested using a sensitivity analysis. Secondly, a case study will be conducted for testing VI as well as the usability of the method.

The components of the method have been implemented in Microsoft Excel workbooks and Visual Basic for Applications (VBA) scripts to perform these tests. I and VI have been implemented separately, and II to V have been merged into a master workbook which integrates the original version of the VBA script and the transition probability matrices published by Richardson *et al.* (2008). This master workbook has the ability to allow calculation of the energy need for SC and DHW for a number of buildings limited by the maximum amount of rows accepted by Microsoft excel 2007 (1.048.576 minus 1 for the labels of every column). It is also able to generate an individual report for every building, which shows the result for every calculation step (e.g. every equation of the customized SCHP for every building component at every hour). This last feature generates a file of approximately 60 mb for every building modeled. This amount of data could be inconvenient when several thousand buildings are to be modeled. Although, using it for a reduced number of test runs has proven to be a valuable tool to check that the code is working properly. Indeed, this and further advantages of model building using excel spreadsheets were already documented in Wainwright and Mulligan (2004)

The strategies adopted for verification of the different models were to check the reports of several test runs using hypothetical examples as well as a careful code-checking. Additionally, with regard to VI, hypothetical cases have been used to check that the script was following the algorithm adequately. For I, the calculation has been tested using reference zone 13 of the TRY (corresponding to Wurzburg, which is usually used as reference climate for Germany) and the results have been examined in detail for at least one random day of every month for each selected direction (North, South, East & West) and inclination (45° and 90°).

4.1. Modeling the German building typologies

Considering that the source of information for the thermal quality of the buildings envelopes is the German typology, and that the calculation procedure used in the TABULA project is the seasonal method also available in the EN ISO 13790:2008 (which should deliver similar results to the SHCP), it is expected that the proposed method is able to predict similar values to the yearly results adapted to consumption obtained in the TABULA project. Additionally, it is also expected that the results approximate the predicted energy need for the model buildings from the German typology, published prior to the TABULA project (see and Born *et al.*, 2003) which is widely used for regional energy use plans at the sub-national level. These two sets of results are not identical, due to the calculation procedure and the assumptions made. In the second case the calculation corresponds to the one consigned in the DIN V 4108-06, and the input data which is not related to the buildings´ envelopes (which is the same in the three cases) is retrieved from the "Energiebilanz-Toolbox" (Loga *et al.*, 2001). In both cases, reduction factors are used to adapt the predicted values to typical consumption values. Nevertheless, in the second case the prediction is also corrected by modifying the internal temperatures to values which follow the description of Loga *et al.* (2001), which is also the source for the assumptions made about the internal temperatures in the proposed method.

Comparing the results between the proposed method and the previously described sources serves to test the suitability of the adopted assumptions for obtaining coherent yearly energy need values. Moreover, similar results show that the proposed method as a unit is working properly. The only exceptions are the GIS related components and the algorithm for classifying the buildings into the typologies that are not necessary in this case, and which are tested in section 4.2.

The conditioned living area, construction year class, number of storeys, type and number of flats in the model buildings of the German typology are the input data for this test for the proposed method[16]. The only missing input information is the number of occupants per flat, which is estimated by dividing the living area of the buildings by the number of flats, then dividing this value by the national average number of square meters of living area per resident; 42,5 m^2 for the year 2010 (Statistisches Bundesamt, 2012).

Predictions of the energy needed for heating are calculated under two different conditions: (i) in their original state, and (ii) assuming a standard refurbishment, as proposed in Loga *et al.* (2011). The energy need for heating of the model buildings from the German typology per square meter obtained with the proposed method is presented in Table 4. Fig. 6 presents the comparison of the percentage differences between the values obtained with the proposed method, and the values obtained from the TABULA project calculations. Additionally, Fig. 7 presents the comparison, between the values obtained with the proposed method and the values published in

[16] available in Loga *et al.* (2011)

Born *et al.* (2003). In this last case, values for the last two year classes (I and J) are not contemplated in the original publication, and therefore a comparison for six of the buildings is not possible.

Type	Without refurbishment	With standard refurbishment	Type	Without refurbishment	With standard refurbishment	Type	Without refurbishment	With standard refurbishment
SFH_A	232,6	93,6	TH_D	220,4	99,8	MFH_F	181,4	84,5
SFH_B	190,2	90,4	TH_E	167,3	89,7	MFH_G	163,4	84,4
SFH_C	171,4	84,1	TH_F	162,5	88,5	MFH_H	162,7	75,8
SFH_D	158,0	94,3	TH_G	117,1	81,8	MFH_I	100,5	108,8
SFH_E	125,1	82,3	TH_H	105,5	64,5	MFH_J	48,1	51,2
SFH_F	161,5	91,9	TH_I	67,1	82,1	AB_B	131,6	68,9
SFH_G	112,3	65,6	TH_J	45,5	48,8	AB_C	162,1	68,0
SFH_H	108,3	80,6	MFH_A	207,1	82,3	AB_D	177,8	72,6
SFH_I	78,8	95,4	MFH_B	134,4	68,1	AB_E	126,2	58,3
SFH_J	62,3	66,8	MFH_C	154,2	65,4	AB_F	121,2	58,2
TH_B	162,3	76,5	MFH_D	236,4	95,3	AB_EE	113,8	48,5
TH_C	215,7	91,3	MFH_E	158,8	67,9	AB_FF	107,6	47,6

Table 4. Energy need for heating per square meter of living area using the proposed method for the model buildings in the German typology.

The first comparison (Fig. 6) shows three relevant facts. Firstly, there are five cases of overestimation above 40 %. Secondly, the buildings in year class J show the highest underestimation, also close to 40%. Thirdly, most of the predicted values remain at a variation bandwidth of 20% (standard deviation of 23, 95%), and their mean and median are -1% and -5,4% respectively.

The values of the measures of central tendency are in very satisfactory ranges, and the apparently high variations of the first two facts are plausible, since the differences only in the input data added together can easily reach these values. Only from the procedure for determining the areas of building envelope components´ are variations of up to +23% and -20% expected. Additionally, variations of around 20% are expected from the input temperatures (between 16°C and 23°C), assuming a simple proportional approach (in the case that the effect would be 1 to 1). Further reduced variation is expected from the climate data and the way in which night and weekend set backs are accounted for. Finally, a certain degree of overestimation is expected from the proposed method, because there is no reduction factor for components such as multilayered wallpaper, wood paneling on the exterior walls, carpets, cabinets and other building components that are considered in the calculation made in the two sources used for comparison.

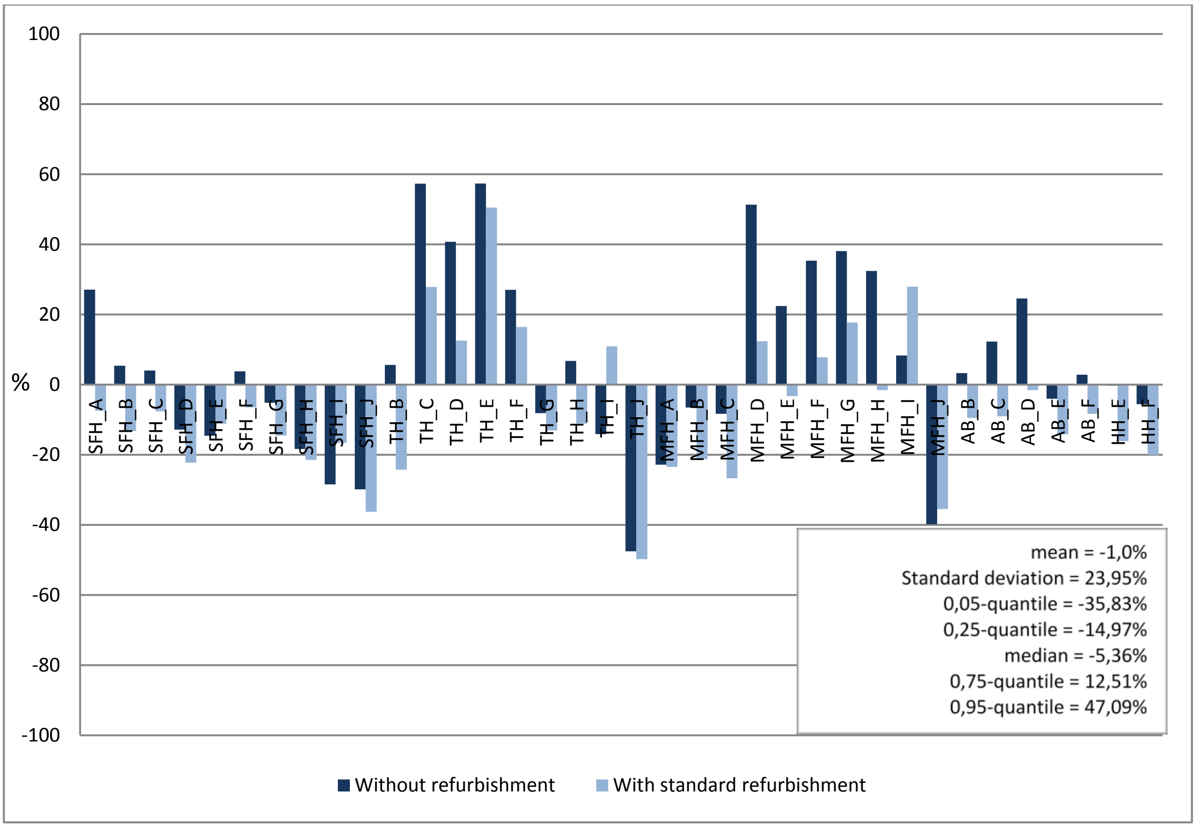


Fig. 6. Percentage differencess for the yearly energy need for heating per square meter obtained with the proposed method under average German climatic conditions, and the TABULA results corrected to consumption values for the German Building typology.

However, in the case of the buildings from year class J, the results are counterintuitive considering that for the proposed method a heating set-point temperature of 23°C is used. This leads to the expectation that an overestimation might take place. This problem was checked in detail for the six cases (SFH_J, TH_J and MFH_J with and without refurbishment) and it was found that the areas of the buildings´ envelope components were severely under estimated. Therefore, energy loss due to transmission is very low compared to the reference cases, which leads to strongly reduced values for the energy need prediction.

This problem could be partly supported by the fact that the procedure for determining the areas of buildings´ envelope components was developed in 2005, and certainly with older data, while the starting year of year class J is 2002. That would mean that this class is completely under represented, and that the prediction could generate values with even larger differences than those expected for the rest of the year classes. Unfortunately, no better procedure for predicting the areas of the building´s envelope components could be found.

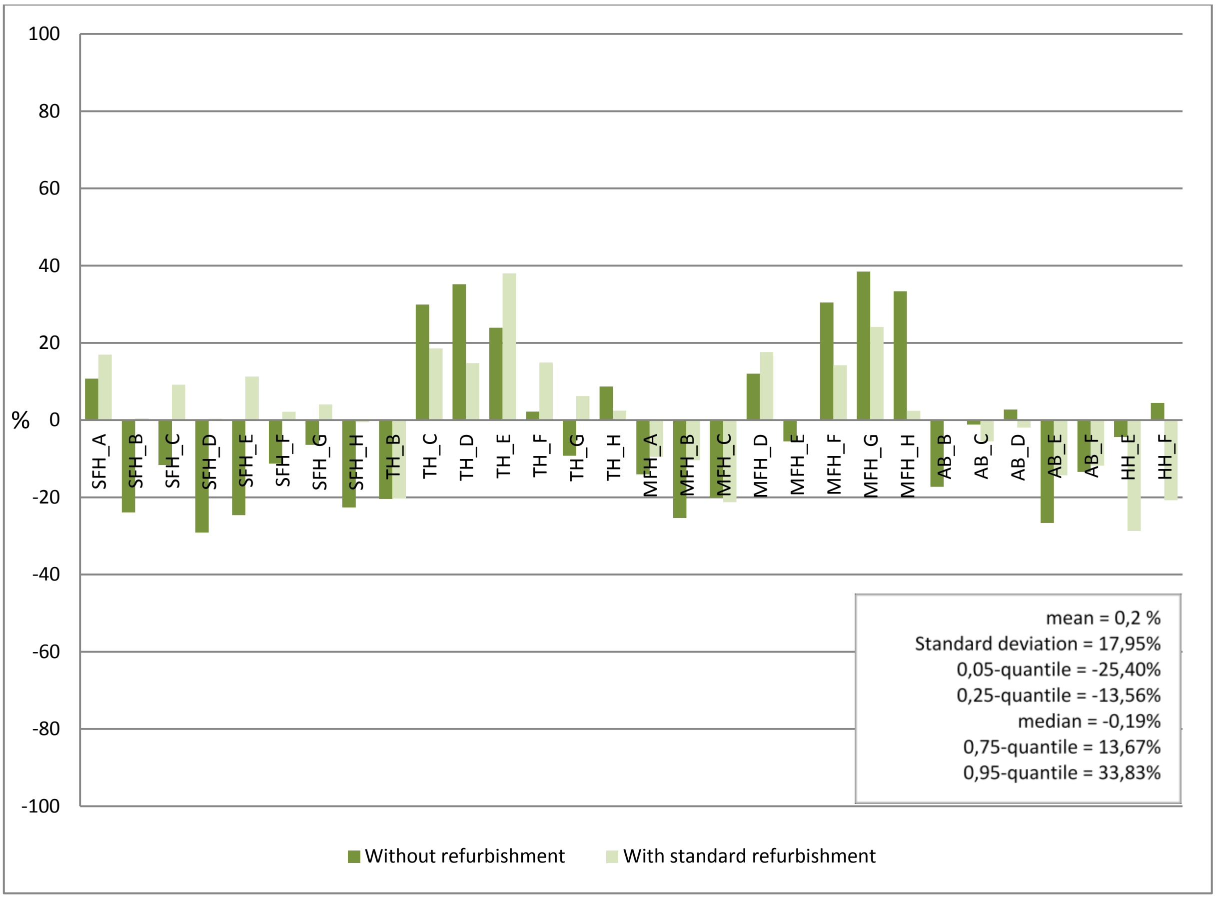


Fig. 7. Percentage differences of the yearly energy need for heating per square meter obtained with the proposed method under average German climatic conditions and the national reference values corrected to consumption for 30 of the basic buildings of the German typology.

The second comparison presents better results than the first comparison. Mean, median and standard deviation are closer to 0% variation, and in the extreme cases over 40% difference also disappears. In the case of under estimations (identified in the first comparison), no comparison can be made due to there being missing data for the last two year classes in the original publication. Such a level of agreement is also expected since the input data for the calculations performed in Born *et al.* (2003) have even more in common with the proposed method than in the case of the TABULA project.

Additionally, several runs were made for the set of buildings in the German typology, under exactly the same conditions for testing the impact of the occupancy patterns that are generated each time for every household. The mean of the differences of the yearly values between runs is at approximately (plus or minus) 1%, with a standard deviation of around 2,1 %. This shows that although there are differences in the hourly basis, when seen throughout the whole year all occupants have a typical behavior.

To summarize, the proposed method with its assumptions and integrated components is able to generate yearly predictions of energy need for heating of individual buildings that are consistent with sources that are widely used in the German context.

In the case of yearly DHW, the only intention was that assumptions adopted were consistent with standard values. There are two standardized values for the yearly energy need for DHW per square meter for domestic buildings: 10 kWh/ m^2 for SFH and 20 kWh/ m^2 for MFH (CEN, 2008). The results obtained for the set of buildings in the German typology using the proposed method are presented in Table 5.

The set is divided into two groups: One to be compared with the standard value of SHF corresponding to the SFH and TH, and other to be compared with the standard value for MFH, which corresponds to the MFH, AB and HH.

The results remain in a range between the two standard values. Nevertheless, the values for SFH and TH are closer to the standard value for MFH than the value for SFH. This situation has an explanation due to the fact that the number of occupants for all buildings was determined using the same national average living area per occupant. A statistic that differentiates the areas for SFH and MFH or the actual number of occupants would contribute to the drawing nearer of the differences between the yearly predicted values and the standard values. In the case that this information is not available, the predicted yearly values presented here are a confirmation of the concordance between assumptions which allow for the generation of an hourly energy need pattern for DHW and typical standard values.

Finally, the energy need for cooling in the domestic sector is a topic that has not received much attention in Germany due to climatic conditions and the consequently modest participation in aggregated energy consumption[17]. In 2009, the energy for cooling represented about 4% of the entire final energy demand of the German domestic sector. It is about 4,72% when compared to the energy demand for heating and DHW (RWI, 2011). However, the proposed method also delivers the values for the energy need for cooling. When calculating this need for the buildings in the German typology, on average 4,2% of the energy need is required for heating and DHW, with a standard deviation of 4,17%.

There are no alternatives for a detailed comparison. But, considering that the SHCP is tested to be capable for accurate predictions for the energy need for cooling, the results obtained with the proposed method could be used as an illustrative reference. Moreover, although the energy need for

[17] There is not even a European standard for computing cooling degree days (Olonscheck *et al.*, 2011)

cooling for the domestic sector does not play a practical role nowadays, the proposed method can for example be used to predict the role that climate change would play in terms of this energy requirement. That type of prediction can be made by using the data for the predicted climate conditions in 2050 which are included in the TRY. Further studies concerning urban density can also be performed using the proposed method, since the last version of the TRY can also take into account changes in the climatic conditions generated by different settlement configurations.

Type	Energy need for DHW per m^2	Type	Energy need for DHW per m^2
SFH_A	17,06	MFH_A	16,54
SFH_B	15,81	MFH_B	19,13
SFH_C	14,82	MFH_C	15,53
SFH_D	20,17	MFH_D	21,27
SFH_E	14,03	MFH_E	15,28
SFH_F	17,25	MFH_F	25,51
SFH_G	13,86	MFH_G	20,57
SFH_H	14,92	MFH_H	19,20
SFH_I	18,39	MFH_I	21,48
SFH_J	15,30	MFH_J	19,45
TH_B	15,58	AB_B	19,82
TH_C	19,88	AB_C	15,10
TH_D	14,98	AB_D	18,65
TH_E	19,10	AB_E	18,45
TH_F	14,06	AB_F	21,59
TH_G	20,71	HH_E	24,67
TH_H	17,57	HH_F	19,16
TH_I	15,06	Mean	19,49
TH_J	14,76	Median	19,32
Mean	16,49	Standard deviation	2,95
Median	15,58		
Standard deviation	2,23		

Table 5. Energy need for DHW per square meter living area using the proposed method for the model buildings in the German typology.

4.1.1. Sensitivity analysis

Sensitivity analysis (SA) is a widely accepted tool for studying the model output sensitivity to variations in the input data. This tool is usually used to check model logic, robustness of simulations and to define the importance of model parameters (Wainwright and Mulligan, 2004), and for some authors, SA is even a condition *sine qua non* for model building (Saltelli *et al.*, 2000b) .

There are several techniques which are used to perform SA. More than a dozen of them were already reviewed almost two decades ago in Hamby (1994) and, more recently, an exhaustive study was made in Saltelli *et al.* (2000a) . Despite there being further developments and improvements in computational capacities, the most simple and limited approaches: Local and One-at-a-time (OAT) SA are still the most commonly used in environmental and natural sciences (Saltelli, 2002). In the field of bottom-up models for predicting the energy consumption of domestic buildings the situation is not different, the only publications dealing with the uncertainty of the models, Kavgic *et al.* (2010) and Firth *et al.* (2010), made use of local SA.

Regardless of their simplicity and popularity, "local analyses cannot be used for the robustness of model based inference unless the model is proven to be linear (for the case of first order derivates), or at least additive (for the case of higher and cross order derivates)" (Saltelli and Annoni, 2010, p.1509). In the case of Firth *et al.* (2010) the model was proven to be linear and additive, but the analysis was performed for a very narrow space of input change (+/-10%) thus limiting the relevance of the results within this restricted space (Kavgic *et al.*, 2010). Kavgic *et al.* (2010) used a wider space of input change, but the model was non linear and non additive. The consequence of the lack of these two characteristics is that the calculated sensitivity of the input variables holds and is informative only for the base case and not for the rest of the space of input factors (Saltelli and Annoni, 2010).

Global SA based in regression techniques represents an alternative to deal with the limitations of local SA at no additional computational cost (Ibid). The use of regressions allows for the examination of the sensitivity of the output of a model to changes in the whole spectrum of changes within the input parameters without requiring additional re-runs of the model (Saltelli and Annoni, 2010; Saltelli *et al.*, 2000a).

A Least Squares based Regression Analysis is used to test the proposed method. The Least Squares Method is widely used, and detailed descriptions of it can be found easily elsewhere[18]. Very briefly, the basic idea behind the least squares method is to fit a model to a set of observations, where the criterion for fitting is the minimization of the sum of the squares of the difference between the fitted and the observed values (residuals). The (linear) model to test the proposed method is presented in equation (44).

[18] Saltelli *et al.* (2000a) explain the minimum requirements for using the Least Square Method for sensitivity analysis, and also recommended a series of workbooks dealing with the topic on the page 123. An explanation of the very basics can also be found in Johnston and DiNardo (2007).

$$\frac{E_{SC+DHW}}{A_f} = b_0 + b_1 A_f + b_2 \frac{n_{O,act}}{A_f} + b_3 \theta_{int,HC,set} + b_4 \theta_e + b_5 n_{neigh} + b_6 refurbishment + b_7 n_{VG} + b_8 A + b_9 B + b_{10} C + b_{11} D + b_{12} E + b_{13} F + b_{14} G + b_{15} H + b_{16} I \qquad (44)$$

Where, $\frac{E_{SC+DHW}}{A_f}$ is the total energy need for SC and DHW per square meter of certain building in a certain hour of the year, letters A to H represent dummy variables for the year classes. I.e. the number 1 in one of these variables represents that the building belongs to this year class, and 0 in all year classes means that the building belongs to year class J. The "refurbishment" variable is also a dummy in which 1 means that the building possesses a conventional refurbishment and 0 means that the building is still in its original condition. A_f(conditioned area), n_{neigh} (number of neighboring buildings) and θ_e (external temperature) are basic input requirements for the method which can be used for the regression in exactly in the same form that they are used for the proposed method. The basic input variable corresponding to the total number of occupants is not included because it was calculated as a factor of A_f and perfect collinearity is expected. In its place $n_{O,act}$ (Amount of active occupants) is included, and the value per square meter is calculated to encompass the dependent variable. A further variable that does not belong directly to the basic input requirements for the proposed method is $\theta_{\text{int,HC,set}}$ (The temperature set point for heating or cooling), which is an intermediate step of the SHCP. This inclusion is required to deal with a situation that neither Firth *et al.* (2010) or Kavgic *et al.* (2010) or other modelers using a calculation procedure only concerning heating on a yearly basis have to contemplate. For them the heating set point is always the same. They usually assume that it is heated for the whole period, and they also do not consider cooling temperature threshold or cooling set point. With the proposed method, these temperatures can change every time-step; and that is precisely what the variable $\theta_{\text{int,HC,set}}$ should represent.

The applicability of the results which can be obtained through this model for further building stocks is limited to the assumption that the types assigned to the buildings of the specific building stock are distributed equally to the distribution of the types in the German typology. I.e. that the same amount of buildings belong to each type, and that all types should be represented. The model and the process described here could be seen as a template which can be replicated easily for each particular building stock.

The open source program R (R Core Team, 2012) has been used for the regression analysis. The results of the regression are in Table 6.

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	1,106e-02	5,825e-05	189,80	<2e-16
Conditioned_area (A_f)	1,559e-07	8,320e-09	18,74	<2e-16
Active_occupants ($\frac{n_{O,act}}{A_f}$)	5,563e-01	1,654e-03	336,44	<2e-16
Theta.air.set ($\theta_{int,HC,set}$)	3,948e-04	1,674e-06	235,91	<2e-16
Temp_extern (θ_e)	-8,717e-04	1,482e-06	-588,11	<2e-16
Number.of.neighbours (n_{neigh})	-4,430e-04	1,771e-05	-25,01	<2e-16
refurbishment	-9,673e-03	2,532e-05	-381,98	<2e-16
Storeys (n_{VG})	-7,197e-04	8,738e-06	-82,36	<2e-16
A	1,476e-02	6,867e-05	214,96	<2e-16
B	8,842e-03	5,955e-05	148,46	<2e-16
C	1,028e-02	5,687e-05	180,77	<2e-16
D	1,081e-02	5,713e-05	189,20	<2e-16
E	8,268e-03	5,687e-05	145,38	<2e-16
F	7,934e-03	5,616e-05	141,27	<2e-16
G	6,327e-03	6,064e-05	104,35	<2e-16
H	5,093e-03	6,016e-05	84,66	<2e-16
I	4,070e-03	6,052e-05	67,24	<2e-16
Residual standard error: 0,009731 on 630703 degrees of freedom				
F-statistic: 4,745e+04 on 16 and 630703 DF, p-value: < 2,2e-16				
Multiple R-squared: 0,5462, Adjusted R-squared: 0,5462				

Table 6. Results of the regression analysis

The signs which are shown in the obtained regression coefficients reveal that the proposed method is working logically. In general the variables have a behavior which is consistent with knowledge about energy need for heating, the explanation for this is the relatively low proportional participation of energy need for cooling and DHW in $\mathrm{E_{SC+DHW}}$.

The dummy variables, letters "A" to "I" represent just one single variable: the year class of the building. The coefficients show how the energy need increases when a building corresponds to previous periods compared to year class J. In general the coefficients follow an expected trend. The lowest difference exists in year class I and it increases almost progressively until it reaches the largest difference, year class A. In other words, the coefficients show that older buildings have a greater energy need than more modern buildings.

The variable "Storeys" (n_{VG}) shows a negative relation to $\frac{\mathrm{E_{SC+DHW}}}{A_f}$. Buildings with a higher number of storeys are typically buildings with more flats (MFH and AB), and the fact that these buildings require less energy for heating per square meter than their smaller counterparts (SFH) is widely recognized. In the case of energy need for DHW, the fact is that the relation between these variables is positive. Nevertheless, the calculation for the amount of occupants based on the living area of the buildings does not really represent a wide differentiation between the consumption in SFH and MFH. Thus, the relation of "Storeys" to the energy need for DHW is certainly undermined and not reflected in the regression coefficient.

The negative relation between the dummy variable "refurbishment" and the dependent variable agrees with the fact that refurbished buildings require less energy for heating per square meter than non refurbished buildings (assuming occupants that behave similarly).

In the case of "number.of.neighbours" (n_{neigh}), the sign indicates that a higher number of neighboring buildings reduces the hourly energy requirement per square meter. This is the case for the THs, where energy need for heating is lower due to the heat exchange with attached buildings. This exchange is not explicit in the customized SHCP (adiabatic boundaries are assumed for each building), but the calculation procedure for determining the areas of the elements of the building envelope reduces the area of the walls depending on the number of neighboring buildings. Such a situation leads to lower transmission losses/gains, and therefore to reduced energy need.

The signs of "Temp_extern" (θ_{e}) and "Theta.air.set" ($\theta_{int,HC,set}$) reflect entirely the situation for the heating period. The lower the external temperature, the more energy for heating is required, and an higher heating set point leads to higher the energy need for heating.

Concerning "Active_occupants", $\left(\frac{n_{O,act}}{A_f}\right)$, the positive relation reflects mostly that the energy need for heating exceeds the internal heat gains from persons, appliances and lighting when persons are active during the heating period. Additionally, this relation could be interpreted as the direct relation that exists between the requirements for DHW and the periods of activity of the occupants. It is also coherent with the idea that buildings require more energy for cooling when persons are active and appliances are in use during cooling hours.

Finally, the sign for "Conditioned_area" (A_f) would mean that larger buildings have a greater energy need per square meter. This result is counterintuitive and also goes against the results obtained for the "Storeys" variable. However, coefficient b_1 is the lowest of all coefficients, and in practice $1{,}559 * 10^{-07}$ means that a change of 10.000m^2 would increase the energy need by 1,5 Wh in a given hour per square meter. Considering that the mean total energy need in one hour is 15,2 Wh/m^2 and that 75% of the buildings have an area of under 755,25 m^2, it is possible to affirm that the effect of the variable "Conditioned_area" is almost neutral (as it should be, since the dependent variable is already corrected by A_f) .

Due to the differences in the magnitudes of the coefficients and variables, a comparison of the importance of the variables is not possible when using the results of this simple regression analysis. Standardized Regression Coefficients (SRCs) can be used to provide a measure of importance for the variables. To obtain the SCR, the dependent and independent variables are normalized to a mean of zero and a standard deviation of one (Saltelli *et al.*, 2000a). The coefficients resulting from the regression of the normalized variables can be compared with each other. Each coefficient represents the effect of a change with a magnitude equal to one times the standard deviation of the variable on the standard deviation of the dependent variable, while all other variables are maintained unchanged.

All the variables in equation 44 (except for the dummy variables) were normalized. The result of the regression is presented in table 7.

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0,1973214	0,0030968	-63,72	<2e-16
Conditioned_area (A_f)	0,0361356	0,0019279	18,74	<2e-16
Active_occupants ($\frac{n_{O,act}}{A_f}$)	0,3059354	0,0009093	336,44	<2e-16
Theta.air.set ($\theta_{int,HC,set}$)	0,2178982	0,0009236	235,91	<2e-16
Temp_extern (θ_e)	-0,5087763	0,0008651	-588,11	<2e-16
Number.of.neighbours (n_{neigh})	-0,0248520	0,0009936	-25,01	<2e-16
refurbishment	-0,6696083	0,0017530	-381,98	<2e-16
Storeys (n_{VG})	-0,1615931	0,0019620	-82,36	<2e-16
A	1,0218867	0,0047538	214,96	<2e-16
B	0,6120479	0,0041225	148,46	<2e-16
C	0,7116925	0,0039370	180,77	<2e-16
D	0,7481997	0,0039545	189,20	<2e-16
E	0,5723517	0,0039368	145,38	<2e-16
F	0,5492491	0,0038879	141,27	<2e-16
G	0,4380154	0,0041976	104,35	<2e-16
H	0,3525837	0,0041649	84,66	<2e-16
I	0,2817278	0,0041897	67,24	<2e-16
Residual standard error: 0,6736 on 630703 degrees of freedom				
F-statistic: 4,745e+04 on 16 and 630703 DF, p-value: < 2,2e-16				
Multiple R-squared: 0,5462, Adjusted R-squared: 0,5462				

Table 7. Results of the regression analysis with SRCs

The results of the SRCs are very similar to that of the regression with non normalized variables. The signs which are shown in all the coefficients remain the same, except for the intercept. The dummy variables explaining the year class also maintain their crescent trend between I and A; and therefore the earlier intuition about "Conditioned_area" is confirmed. In fact, the impact of "Conditioned_area" is 436% lower than the impact of "Storeys" and thus, the agreement of the proposed method with the fact that the energy need per square meter of larger buildings is lower, has been proven again.

Most of the dummy variables of the year class present a higher impact, but they cannot be interpreted in the same way as the rest of the variables in the model. In this case, the coefficient shows the effect of the situation of a building in a certain year class on energy need. This means for example, that if a building is classified in year class A instead of class J, the value for energy need is 1,021 times its standard deviation larger. However, the impact of changing the classification between classes which are consecutive (e.g. I to H or H to G) is much lower, and remains at around 0,14 (which is the mean of the absolute difference of the SCRs between each one of the consecutive classes).

The following variable with an important impact is “refurbishment”. Its relevance was already evident in the yearly results of the predicted energy need for heating presented in Table 4. However, this result should be interpreted carefully because depending on the building stock its importance could change radically. As seen in Table 4, the difference between standard refurbished and non refurbished buildings decreases when the buildings are newer. This means that for a building stock composed mostly of older buildings the determination of the level of refurbishment plays certainly a very important role, while for a building stock of mostly modern buildings this information could become irrelevant. This situation is not reflected in the SCRs of the results for the model buildings of the German typology because all building types are equally represented. What can be extracted from the SRCs is that “refurbishment” is an input variable that should be treated carefully, and that it is a topic which the user of the proposed method should be aware. Moreover, the objective of this variable is that it be used for scenario building and not necessarily for the actual prediction of energy need.

Concerning the variables, “Temp_extern” is shown to be the variable with highest relative impact, followed by “Active_occupants” and “Theta.air.set”. Variables with the lowest impact are “Storeys”, “Number.of.neighbours” and “Conditioned_area”. This shows that climatic conditions and the behavior of occupants play a major role in the total energy need per square meter, rather than geometric and neighboring conditions of buildings. Moreover, the variables concerning human behavior when summed together represent a major impact on energy need per square meter as well.

The “Multiple R-squared” (R^2) or coefficient of multiple determination is an indicator for the goodness of fit of the model to the data. In the case of regression based sensitivity analysis, the R^2 can be seen as the indicator of how successful the model is in accounting for the uncertainty in the dependent variable (Saltelli *et al.*, 2000a). R^2 can take a value between zero and one. One represents that the model account for all the uncertainty in the dependent variable. Zero represents that the model does not have any success in accounting for that uncertainty. In the case of the evaluated model, both runs (with non-normalized and with normalized variables) have an $R^2$of 0,5452, and account for approximately 54% of the uncertainty in the prediction of $\frac{\mathrm{E_{SC+DHW}}}{\mathrm{A_f}}$. Considering that the primary input variables (or their representation) only make up approximately 15% of the total amount of all the input variables, the obtained R^2 is fairly satisfactory.

Conventionally, an alternative to continue to test the quality of the model is to determine the significance of the regression coefficients. Usually, two different tests are used: (i) an F-statistics: to show the significance of the overall fit. And (ii) a t-statistics: to assess the significance of every single regression coefficient separately.

In this case, both runs of the model to test the proposed method show very similar results. The p-value of both the F-test: for the whole model, and t-tests: for each coefficient, are much smaller than 0,001. Thus, the regression coefficients can be labeled as highly significant.

Unfortunately, this typical interpretation cannot be adopted straight away if a normal distribution of the residuals cannot be assumed. This is for example the case in sampling-based sensitivity studies with deterministic models, where a given input parameter (or set of input parameters) always produces the same output (Saltelli *et al.*, 2000a). It is also the case for the model used to test the proposed method. However, in both of these cases the results of the statistical test are still useful since they serve as an indication of "how viable the relationships between input and output variables would appear to be in a study in which the underlying distributional assumptions were satisfied" (Ibid, p.128).

Further steps for typical regression analysis, such as the selection of the best possible model are not expected to deliver more relevant information. However, the robustness of the method, defined as its ability to handle a variety of situations with a limited loss of accuracy (CEN, 2008) should be still discussed.

Although variables have an important explanatory value, a series of arguments are presented to support the idea that there is no specific one which could have an impact large enough to jeopardize the results when using the method:

- In the case of the dummy variables representing the construction year classes, the major prediction error that could be made would be where a building is classified in the J class but actually belongs to the A class or vice-versa. The fact is that there are specific typologies for almost all regions in Germany (Born *et al.*, 2003), and even with missing construction years for buildings, the statistics behind the regional typologies could be used to delimit possible errors. Missing the year class for one class changes the energy load required for an entire hour by a rate of around $2W/m^2$ [19](which is only a fifth of the maximum permissible heat load for the certification of a passive house).

[19] Result of multiplying the mean of the absolute difference of the SCRs between each one of the consecutive classes (0,14) and the standard deviation of the total energy need per square meter in one hour (14,4Wh/m^2) or simply the mean of the absolute difference of the non normalized regression coefficients multiply by 1.

- The variable corresponding to the external temperature has a very high impact but the value for a certain hour of the year is not expected to change because it is taken directly from the TRY. The quality of this data is expected to be very high, as it is also expected that the selected stations are effectively representative of the defined regions.

- The next variable is the amount of active occupants per square meter. This variable has two mayor sources: The total amount of occupants, and the stochastically determined amount of active occupants; It was shown that in the absence of the actual total amount of occupants per building, the national average living area per person can be used reversely in order to determine the amount of occupants without drastically affecting the annual total energy need prediction. Although the effect of this source is theoretically very limited since the interest variable was corrected by dividing it by the reference area. The algorithm behind the second source delivers permanently consistent results and there is no reason to consider that it could turn into a source of additional uncertainty (Additionally, the accuracy for the annual results, and logical behaviour for the hourly values were tested).

- The variable for the temperature set points also has two sources. One is the international standard for the cooling set point; this is equal in all cases. The second: The selected heating set points, are supported by statistically tested data. These values differ in terms of their actual values; the only known better data source would be to contact the occupants of the buildings directly. In any case, missing actual values per 8°C (standard deviation of the variable) would change the output variable by merely $3W/m^2$ (which is the standard deviation of the output variable multiplied by the SRCs of the temperature set points).

- The geometric variables as well as the neighboring situation of the buildings have shown to be necessary and explanatory. But, changes in its values have a reduced impact on the output. The most interesting participation of these variables should take place in the algorithm used to classify the objects of a building stock to match the German typology. The accuracy of this algorithm is yet unknown, but tested in the next section of this thesis.
- The problem with the level of refurbishment is well known: There is poor systematic documentation, and there are high costs to raising the data. The proposed use for the conventional refurbishment is to develop scenarios. Furthermore, information about refurbishment can always be included in the calculation procedure as well as assumptions about the refurbishment rate of the specific building stock.

To summarize, the input variables are necessary and explanatory for the results of the method. Additionally, changes in the values of these variables are not expected to drastically modify the results or even no variation in the values is expected when applying the method to further building stocks. Nevertheless, there is an exception to the rule: The refurbishment measures posses a relatively high impact. The information about the refurbishment of buildings is usually not available, the treatment option is to use the variable as a source for building scenarios. In the case information about refurbishment measures of particular buildings becomes available the method is able to account for it by modifying the corresponding input variables (u-values, thermal bridges, etc).

4.2. Case Study Analysis

The major objective of performing this case study analysis is to show that the proposed method is able to effectively predict the hourly energy need for SC and DHW of an administrative unit on the sub-national level by using only reduced input data, and therefore there are no special conditions that the object of study should fulfill. However, the case study analysis has a second objective. It is to prove the accuracy of the algorithm to classify the objects of a building stock to match the German typologies, and in this case detailed information about the type of the buildings is necessary for comparison.

The case study analysis is performed with information from Freyung, the capital of the Bavarian municipality of Freyung-Grafenau. It is located in lower Bavaria, in the Bavarian forest, 17 km from the German border with the Czech Republic and 27 km from Passau (the next major city in Germany). The data was provided by the Bavarian land surveying office (“Bayerische Vermessungsverwaltung”) and the construction authority (“Bauamt”) of the local government.

4.2.1. Input data and pre-processing

The regional land surveying office provided shape data with a rough division of the municipality in diverse land uses, and geo-referenced data that present every single building as an independent object. Additionally, a text file linking the coordinates with the addresses of the buildings also was provided.

The construction authority made two data packages available. The first one included 2623 flashcards with the addresses, the year of the connection to the sewage channel system (these usually correspond to the construction year of the building). In some cases the cards give information about the use and characteristics of the properties. Each flashcard was saved in an individual Microsoft-excel workbook in a standardized format, and therefore a Visual Basic script was written to automatically extract the relevant information.

The second data package included building information, which in most cases is information about the type of building and the external area of every storey (Indirectly every entry also included the number of storeys of the building). These data were collated on an MS-excel workbook with a total of 2401 entries, requiring intensive processing and revision, until it was possible to present them in a usable form. A java script was written to extract and organize the pertinent information, and a manual check was required to correct and organize peculiarities in certain entries.

The land use data, the objects and the addresses were joined using ArcMap. Objects belonging to zones entirely dedicated to “industry and businesses”,” sports, leisure and recreation” ; and other “special uses” were discarded. That filtering resulted in a total of 1959 potentially domestic buildings. The information about these remaining buildings was then also joined to the other data sources by using their addresses.

A further filtering process to select only domestic buildings was performed. From the flashcards, it was possible to confirm that 241 buildings (16 in areas of domestic use and 225 in areas of mixed use) belong to other uses, including public property and buildings for commercial and agricultural production purposes. Additionally, it was possible to determine that 42 buildings are annex buildings, such as barns and parking garages using the second package of information from the construction authority. Moreover, 8 buildings did not appear in the information provided by the construction authority, and for further 76 buildings, located in the most distant areas of Freyung the flashcards were empty. They were also not registered in the second data package. The final result is a total of 1592 objects which were identified as domestic buildings. They are presented in Fig. 8.

For most of the buildings the year of connection to the sewage channels was assumed to be the construction year. Nevertheless, flashcards for 113 buildings only appointed that the building was connected to sewage channels before 1960[20]. A secondary source was used to fill this gap in the information. When developing a domestic building typology for Bavaria, Hinz (2006) determined that most of the building stock has been constructed since 1949. This year was assumed as the initial construction year, and therefore the remaining buildings were classified in the class D (1949 to 1957).

[20] The data providers confirmed that this year marks the entry into service of the registry.

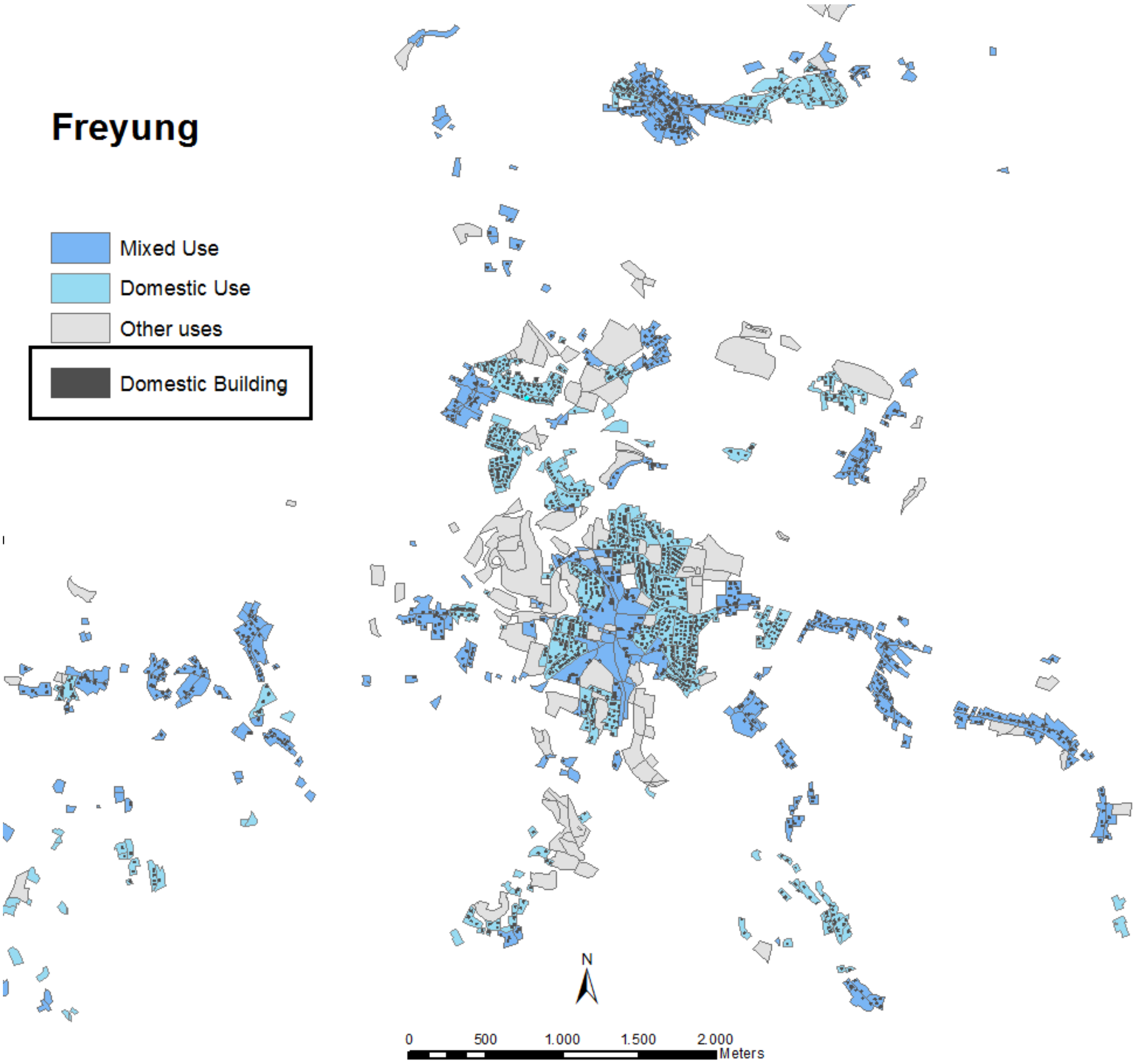


Fig. 8 . Freyung: Selected land uses and domestic buildings (Based on Geobasisdaten © Bayerische Vermessungs-verwaltung 2012)

To determine the living area and the area of the elements of the building envelope the procedure proposed in section 3.2.3 was followed. However, information about attics and basements was available from the second package of information from the construction authority. This was used instead of the information on the German typology in order to estimate the area of elements of the building envelope. The number of storeys was also retrieved from this source.

The geo-neighbor-analysis proposed in section 3.2.1 was used in the first instance to determine the number of neighbours of each building (information necessary to complete the estimation of the areas of the building envelope components) and posterior, as also described in 3.2.1, as a basis to match the buildings to the German typology. The results of this process are presented and discussed in section 4.2.2.

Finally, the number of flats was not available and was determined by dividing the conditioned living area of every building by the amount of square meters that a flat in the given building type possesses (based on the model buildings of the German typology). In the case of the MFH_E, AB_E, HAB_E and AB_F, HAB_F, where no differentiation is made in the classification, the mean area (one for E and one for F) was used. The number of occupants was determined using the local statistic for the average living area per inhabitant, $49\ m^2$ for 2008 (StMWIVT, 2008), and was limited to six occupants per flat[21].

4.2.2. Spatial and temporal model of the energy need for SC and DHW of Freyung.

The algorithm to classify the objects of the building stock to match the German typologies generates the classification presented in Fig. 9. These results were compared with the information available in the second data package obtained from the construction authority, where for every building a description of the type was given.

Exactly 34 of the buildings (2% of the total) were classified incorrectly. 28 of them were classified as SFHs while they are actually MFHs. The explanation for this is that these buildings have a number of storeys inferior to the typical number of storeys of MFHs. The opposite occurred with 6 buildings. They were classified as MFHs, while they are SFHs. In this case the buildings have more than 3 storeys and the living area is also significantly larger than typical values.

Type	SFH_D	SFH_E	SFH_F	SFH_G	SFH_H	SFH_I	SFH_J	TH_D	TH_E	TH_G	TH_H	TH_I	MFH_D	MFH_E	MFH_F	MFH_G	MFH_H	MFH_I	AB_D	AB_F
Amount	80	317	78	54	315	379	283	12	6	7	4	6	19	14	4	2	3	4	2	3

Fig. 9 Freyung: Amount of buildings in each type of the German typology

The VBA script was run in a computer with an Intel® Core™ i5-2410 CPU 2.30-2.9GHz, 4GB of RAM, and a 7200RPM HDD. It took about 5 hours to obtain all hourly, monthly and yearly results. The calculation time ranged between a few seconds for SFHs and few minutes for the largest buildings. It was possible to confirm that the main factor for this difference is the fact that the occupancy pattern of each flat in a building is calculated independently.

Importing the data to ESRI ArcMap 10.1 took few minutes for yearly and monthly information and more than two hours for the hourly results. Yearly and monthly values for energy need for Heating,

[21] This boundary has been included especially due to 102 Single Family Houses with a living area substantially higher than the average.

cooling, DHW or combinations of these can be visualized rapidly. An example of the yearly energy need for heating and DHW obtained for a random[22] part of the town is presented in Fig. 9.

Working with hourly results becomes very time consuming. Simple commands to change visualization options or simple inquiries could require several hours. Nevertheless, the values for the hourly energy need for heating, cooling and/or DHW can be obtained for singular buildings, blocks, streets or the whole area of study, as shown in Fig. 10.

The use of the time visualization properties in ESRI ArcMap 10.1 also allows for the visualization of a specific hour, or for the possibility to present the development of the energy need during the year. A video showing the course of a year of energy need for heating in Freyung is included in the CD attached to this thesis[23].

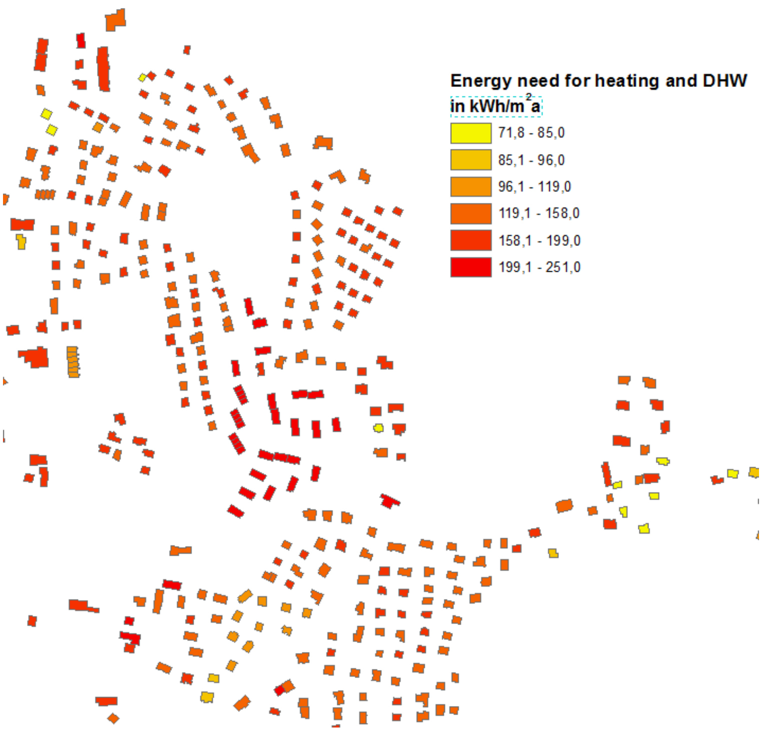


Fig. 10. Energy need for heating and DHW of the domestic buildings of a random area of Freyung

[22] Following StMUG *et al.*, (2011) it would be necessary (for legal reasons) to transform the polygon-based representation of the buildings to a raster representation. This is required to avoid that the presented data could be attributed to particular private persons. However, as can be found for example in Neidhart and Sester (2006), in order to maintain the original resolution of the predictions a random section of the town, without street names or coordinates, and without information about the orientation, is presented.

[23] The video shows values every five hours. The geometric representation of buildings has been changed per points of the same size for each building. Names of streets or coordinates were excluded.

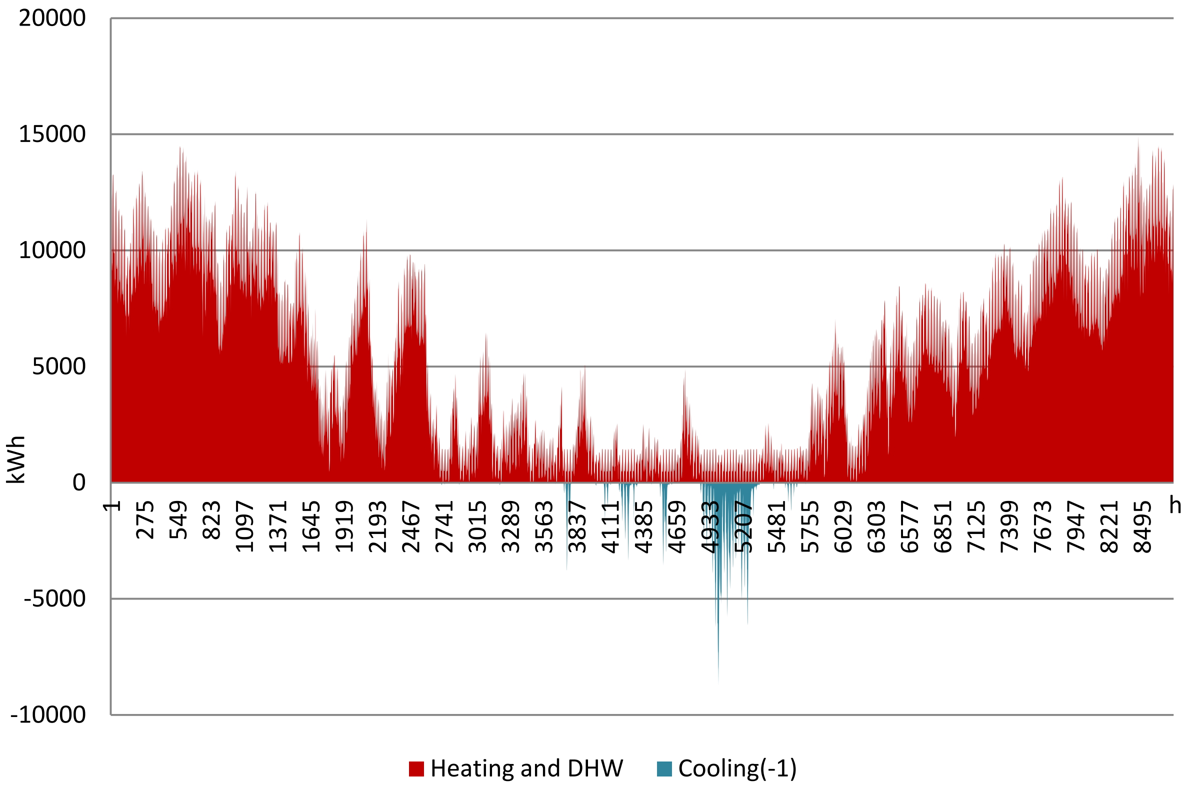


Fig. 11. Hourly Energy need for Heating and DHW, and cooling for all domestic buildings of Freyung

4.2.3. Discussion of the case study

Typically used methods for predicting energy need for heating of domestic buildings in a very high spatial definition for large building stocks, such as proposed in StMUG *et al.* (2011), are limited and can be complicated in the implementation because they require the precise differentiation of building types. Neidhart and Sester (2006) and Schüssler (2010) have shown that the differentiation was impracticable and opted for an own classification of the buildings. The proposed method covers part of this problem with the re-calculation of the energy need of each building, and with the inclusion of an algorithm for the classification of buildings based on the typical characteristics of the buildings in the German typology. A precise differentiation is therefore not necessary for building types with an envelope of similar characteristics. For remaining building types, the case study analysis showed that the algorithm could deliver an accurate differentiation of buildings between SFH, TH, MFH and AB. Only 2% of the buildings were classified incorrectly.

The case study analysis showed that the large amount of output data requires special handling conditions. In the case study area of Freyung, the number of entries per each output variable exceeded the 13 millions, and calculation and post-processing were very time consuming tasks. The amount of data increases proportionally to the amount of objects in a building stock, and the handling of much larger building stocks would likely become completely unmanageable. However, since the case study analysis was performed on an average computer and with software used for standard applications, it is expected that this situation can be much better managed when using higher computational capacities and programs which are optimized to deal with large data sets.

Furthermore, a major restriction that was detected when applying the proposed method was the low input data quality. Three different data sources were needed to be able to show which of the buildings actually are in domestic use. This is the minimum requirement to be able to generate the predictions. If only the official land use map were used, all buildings categorized as in "mixed use" would be excluded due to the lack of detailed information. On the other hand, the inclusion of all buildings of the areas in "mixed use" as domestic buildings would imply that 225 non-domestic buildings would be considered as domestic. For a reduced number of buildings in areas categorized as domestic it was even possible to confirm that they were for other purposes. Another concern is the lack of information of approximately 3% of the buildings of the building stock. These are problems whose impact is essentially not accounted for and would change from case to case. A better data warehousing by the institutions of the administrative units in the sub national level will reduce pre-processing time and will improve the quality of the predictions.

The retrieval of the rest of required input data was also very time consuming, despite of the reduced requirements of the method and the manageable size of the building stock. Improvements in this area are expected in the coming years, since 3D maps including basic information such as the number of storeys are becoming more accessible. The use of this kind of data source will also permit the replacement of estimated with actual information for the areas of the components of the building envelope.

Compared with methods presented in StMUG *et al.* (2011), Neidhart and Sester (2006) or Schüssler (2010), the proposed method is not only able to cope with the highest spatial resolution (predictions for each building) but also offers a high temporal resolution and a series of outputs that are not usually available from other models, i.e. the energy need for cooling, number of heating/cooling hours and the required hourly loads. These outputs are common only in the modeling of individual buildings or reduced building stocks as the examples presented in Kämpf (2009) and Robinson *et al.* (2007). Moreover, the problem with obtaining the information about the level of refurbishment that was reported in all sources dealing with large building stocks was confirmed once again.

In summary, the proposed method offers the simplicity required to model large building stocks but is capable to deliver results that are comparable to very detailed models. The case study analysis served its purpose of showing that the proposed method is able to predict the hourly energy need for SC and DHW of an administrative unit on the sub-national level by using only reduced input data.

5. Conclusions and outlook

A method has been developed and applied to predict the hourly domestic energy need for space conditioning and water heating of the domestic buildings of German administrative units on the sub-regional level (districts and municipalities). Predictions within a very high spatial and temporal resolution can be obtained by relying solely on the living area, neighbouring situation, number of storeys, number of occupants, and construction year of each building.

In order to achieve this simplification of the required input data, a straight-forward but accurate calculation procedure together with an approach based on domestic building typologies were selected. The main calculation procedure is a customized version of the SHCP described in EN ISO 13790:2008. The required input data that concerns the quality of the envelope of each building is taken from the German typology developed by the German Institute for Housing and environment. To classify the buildings of a given stock in order to match these typologies, a simple decision algorithm was developed. The rest of the information required for the calculation procedure is extracted from the TRY, a calculation procedure used to estimate the area of the components of the building envelope, a stochastic occupancy patterns generator, and selected international norms and publications.

The accuracy of most of the components of the method was already tested in its original sources. In spite of this, a verification and validation of the method as a whole has also been performed. The method was used to predict the energy need for heating of the model buildings in the German typology, and the yearly results were in agreement with typically used and widely accepted predictions calculated with other relevant procedures. The yearly values of energy need for DHW are in agreement with standard values, and the predictions of energy need for cooling resemble national averages. The logic of the hourly predictions was tested with a SA which showed that the prediction of hourly variables follows the expected patterns: (i) larger buildings present lower energy need per square meter; (ii) buildings with more neighbouring buildings also have a lower energy need per square meter; (iii) the energy need increases with the difference between the outside temperature and the desired internal temperature; and (iv) the energy need increases with the age of the buildings.

The SA has also served to classify the relative importance and impact of the input variables. Input variables related to climate and human behavior resulted to be more important for the total energy need for SC and DHW than the geometric characteristics and neighbouring situation of the buildings. Additionally, all input variables were shown to have a considerable explicative value, and arguments were presented to support the fact that the method is robust i.e. able to handle a variety of situations with a limited loss of accuracy. Variations in the input data would have an impact on the results, but they would have to be very large to be able to jeopardize the final predictions.

Moreover, the ability of the method to obtain the expected output was tested in a case study analysis. Results for a building stock of more than 1500 objects were obtained in few hours by an average performance computer. High temporal and spatial resolutions are perfectly compatible but high computational capacities are required for proper post processing and analysis. Popular GIS software packages such as ESRI´s ArcGis already support spatial and temporal visualization and analysis but developments in data warehousing are necessary to deal with the large data sets that are generated. Additionally, considering that the calculation procedures were implemented in a mixture between MS excel spreadsheets and Visual Basic for Applications the implementation of the calculation procedures in more efficient programming languages such as C++ should be an alternative to reduce the calculation run-time.

The lack of documentation about the level of refurbishment obligates to use this variable for scenario building. This problem has been documented in several publications and confirmed once again when developing the case study analysis. The lack of other information, such as the construction year or the number of occupants, can be partially filled by using secondary sources which are available for all German regions. Furthermore, the use of LoD2 3D maps should generate improvements in accuracy and can simplify the data acquisition process. These maps include valuable data such as number of storeys, and size and orientation of the components of the building envelope, which will contribute to avoid the use of complementary sources and will serve to replace the predicted areas of the building components with actual dimensions.

Considering that domestic building typologies of a further 12 European countries were developed in the frame of the TABULA project, it would even be plausible to extend the applicability of the method outside the German borders. The only limitation factors are the algorithm to match the buildings of a stock into the typologies and the procedure for calculating the areas of the components of the building envelope, which should be adapted or replaced by local sources.

Finally, the proposed method is a step forward in the procurement of information for planning processes that concern the use of energy and energetic resources. It can be put into action for energy use plans, climate protection plans or to find potential locations for district heating/cooling nets or CHP initiatives. However, there are extensions and enhancements that could be made to the method and its components such as: (i) the prediction can be extended to the primary energy requirements and the related CO_2 emissions. A proper alternative for the prediction of these two values concerning heating and DHW is the use of the energy effort factors of the appliances that are available from the TABULA project. Nevertheless, this option does not exist in the case of cooling, and further research is required; (ii) the method for predicting the energy need of non-domestic buildings could be extended as well. There are still no typologies for this type of buildings but research concerning this issue already is in progress (TABULA Project Team, 2012); (iii) the variability in the energy need due to socio-economic characteristics of the occupants could be included. In order to do this, the probability matrices of the occupancy patterns generator should be modified to include the differences in the daily schedules of the persons belonging to different socio-economic classes, which can be found in the TUS. An interesting alternative to this would be to replace the occupancy pattern generator with a model that is able to consider the seasonal changes such as proposed by Page *et al.*, (2008) but of a level of complexity that allows for its replication; (iv) the integration of SMs which differentiate households by using socio-economic characteristics and/or preferences concerning comfort variables, such as the temperature set points should be considered.

6. References

Andersen, R. V. (2009). Occupant behaviour with regard to control of the indoor environment. Denmark: International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark. [Online]. Available at: http://orbit.dtu.dk/app?cdis=attachment%3B+filename%3D%22Thesis+with+papers++RVA.pdf%22&ctyp=application%2Fpdf&downloadOptionName=URL&service=download_records&url=http%3A%2F%2Furbit.cvt.dk%2Fcgibin%2Furbit_fulltext%2F255801%2F1%2F1%2Fe9f3f785ca6bb994b3364e233ae4fb98 [Accessed: 5 April 2012].

Aydinalp-Koksal, M. and Ugursal, V. I. (2008). Comparison of neural network, conditional demand analysis, and engineering approaches for modeling end-use energy consumption in the residential sector. Applied Energy, 85 (4), p.271–296. [Online]. doi:10.1016/j.apenergy.2006.09.012.

Born, R., Diefenbach, N. and Loga, T. (2003). Energieeinsparung durch Verbesserung des Wärmeschutzes und Modernisierung der Heizungsanlage für 31 Musterhäuser der Gebäudetypologie. Institut Wohnen und Umwelt GmbH. [Online]. Available at: http://www.iwu.de/fileadmin/user_upload/dateien/energie/klima_altbau/GebTyp_Impulsprogramm_Hessen_22_01_2003.pdf [Accessed: 12 April 2012].

Bundesregierung Deutschland. (2009). Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden (Energieeinsparverordnung - EnEV) 2009 Anlage 4: Anforderungen bei Änderung von Außenbauteilen und bei Errichtung kleiner Gebäude; Randbedingungen und Maßgaben für die Bewertung bestehender Wohngebäude. [Online]. Available at: http://www.enevonline.org/enev_2009_volltext/enev_2009_anlage_03_anforderungen_aenderung_aussenbauteile.htm#Anlage%203_Nr_8._Randbedingungen_und_Ma%C3%9Fgaben_f%C3%BCr_die_Bewertung_bestehender_Wohngeb%C3%A4ude [Accessed: 18 April 2012].

CEN, European Committee for Standardization (2008). Energieeffizienz von Gebäuden – Berechnung des Energiebedarfs für Heizung und Kühlung (ISO 13790:2008); Deutsche Fassung EN ISO 13790:2008. Beuth Verlag GmbH..

Cheng, V. and Steemers, K. (2011). Modelling domestic energy consumption at district scale: A tool to support national and local energy policies. Environmental Modelling & Software, 26 (10), p.1186–1198. [Online]. doi:10.1016/j.envsoft.2011.04.005.

Déqué, F., Ollivier, F. and Poblador, A. (2000). Grey boxes used to represent buildings with a minimum number of geometric and thermal parameters. Energy and Buildings, 31 (1), p.29–35. [Online]. doi:10.1016/S0378-7788(98)00074-7.

Deutscher Wetterdienst. (2011). Handbuch zu den neuen Testreferenzjahren 2011 (TRY). [Online]. Available at: http://www.irbnet.de/daten/baufo/20118035316/TRY_Handbuch.pdf [Accessed: 11 September 2012].

Dewson, T., Day, B. and Irving, A. D. (1993). Least squares parameter estimation of a reduced order thermal model of an experimental building. Building and Environment, 28 (2), p.127–137. [Online]. doi:10.1016/0360-1323(93)90046-6.

DS-Plan Gmbh and Institut Wohnen und Umwelt Gmbh. (n.d.). Methodik zur Erfassung, Beurteilung und Optimierung des Elektrizitätsbedarfs von Gebäuden (Handbuch: Excel-Arbeitshilfe Klimakälte). [Online]. Available at: http://www.iwu.de/fileadmin/user_upload/dateien/energie/strom/MEG-Handbuch_Klimakaelte-3.0.pdf [Accessed: 3 July 2012].

EC, European. Comission. (2003). DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings. Official Journal of the European Communities. [Online]. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do? uri=OJ:L:2003:001:0065:0065:EN:PDF [Accessed: 2 May 2012].

EC, European. Comission. (2010). Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings (recast). Official Journal of the European Union. [Online]. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF [Accessed: 2 May 2012].

EPSRC, UK Engineering and Physical Sciences Research Council (2009). The Development of a Local Urban Climate Model and its Application to the Intelligent Design of Cities. LUCID project. [Online]. Available at: http://www.lucid-project.org.uk/ [Accessed: 3 May 2012].

Firth, S. K., Lomas, K. J. and Wright, A. J. (2010). Targeting household energy-efficiency measures using sensitivity analysis. Building Research & Information, 38 (1), p.25–41. [Online]. doi:10.1080/09613210903236706.

Fishman, G. S. and Kiviat, P. J. (1968). The statistics of discrete-event simulation. SIMULATION, 10 (4), p.185–195. [Online]. doi:10.1177/003754976801000406.

Fraisse, G., Viardot, C., Lafabrie, O. and Achard, G. (2002). Development of a simplified and accurate building model based on electrical analogy. Energy and Buildings, 34 (10), p.1017–1031. [Online]. doi:10.1016/S0378-7788(02)00019-1.

Gamerman, D. (1997). Markov chain Monte Carlo : stochastic simulation for Bayesian inference. London; New York: Chapman & Hall.

GBG, Gesellschaft Bauen und Gebäudetechnik. (2012). Berechnung des instationären thermischen Verhaltens von Räumen und Gebäuden Modell der solaren Einstrahlung VDI 6007 Blatt 3. Beuth Verlag GmbH.

Gilks, W. R., Richardson, S. and Spiegelhalter, D. J. (1996). Markov chain Monte Carlo in practice. London: Chapman & Hall.

Grau, K. and Wittchen, K. B. (1999). Building Design System and CAD Integration. In: Sixth International IBPSA Conference (BS'99), Kyoto, Japan, 1999, p.1157–1164.

Haas, R., Auer, H. and Biermayr, P. (1998). The impact of consumer behavior on residential energy demand for space heating. Energy and Buildings, 27 (2), p.195–205. [Online]. doi:10.1016/S0378-7788(97)00034-0.

Haldi, F. and Robinson, D. (2010). The impact of occupants´ behaviour on urban energy demand. In: IBPSA BauSIM, 2010, Vienna, Austria: International Building Performance Simulation

Association German Speaking Chapter. [Online]. Available at: http://www.ibpsa-germany.org/konferenz/paper/ 2010/343.pdf [Accessed: 4 April 2012].

Hamby, D. M. (1994). A review of techniques for parameter sensitivity analysis of environmental models. Environmental Monitoring and Assessment, 32 (2), p.135–154.

Hens, H., Verbeeck, G. and Verdonck, B. (2001). Impact of energy efficiency measures on the CO2 emissions in the residential sector, a large scale analysis. Energy and Buildings, 33 (3), p.275–281. [Online]. doi:10.1016/S0378-7788(00)00092-X.

Hinz, E. (2006). Gebäudetypologie Bayern: Entwicklung von 11 Hausdatenblaetter zu typischen Gebäuden aus dem Wohngebäudebestand Bayerns. Endbericht, Institut Wohnen und Umwelt Gmbh. [Online]. Available at: http://www.iwu.de/fileadmin/user_upload/dateien/energie/klima_altbau/ Bericht_Hausdatenblaetter_Bayern.pdf [Accessed: 13 April 2012].

Howard, B., Parshall, L., Thompson, J., Hammer, S., Dickinson, J. and Modi, V. (2012). Spatial distribution of urban building energy consumption by end use. Energy and Buildings, 45, p.141–151. [Online]. doi:10.1016/j.enbuild.2011.10.061.

Huang, Y. J. and Brodrick, J. (2000). A bottom-up engineering estimate of the aggregate heating and cooling loads of the entire US building stock. Proceedings of the ACEEE Sumer Study on Energy Efficiency in Buildings Conference. [Online]. Available at: http://escholarship.org/uc/item/5hv2t661 [Accessed: 3 February 2012].

ICCS-NTUA, Institute of Communication and Computer Systems of the National Technical University of Athens (2008). European Energy and transport: trends to 2030-update 2007. Belgium: European Commission: Directorate-General for energy and transport. [Online]. Available at: http://ec.europa.eu/dgs/energy_transport/figures/trends_2030_update_2007/energy_transport_trends_2030_update_2007_en.pdf [Accessed: 2 May 2012].

Johnston, J. and DiNardo, J. (2007). Econometric methods. New York, McGraw-Hill.

Jones, P., Lannon, S. and Williams, J. (2001). Modelling building energy use at urban scale. In: 7th International IBSPA conference, Rio de Janeiro, Brazil, August, 2001.

Kämpf, J. H. (2009). On the modelling and optimisation of urban energy fluxes. Lausanne, Switzerland: Ecole polytechnique fédérale de Lausanne EPF. [Online]. Available at: http://infoscience.epfl.ch/ record/141956 [Accessed: 24 May 2012].

Kämpf, J. H. and Robinson, D. (2007). A simplified thermal model to support analysis of urban resource flows. Energy and Buildings, 39 (4), p.445–453. [Online]. doi:10.1016/j.enbuild.2006.09.002

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z. and Djurovic-Petrovic, M. (2010). A review of bottom-up building stock models for energy consumption in the residential sector. Building and Environment, 45 (7), p.1683–1697. [Online]. doi:10.1016/j.buildenv.2010.01.021.

Kiesel, K., Orehounig, K. and Mahdavi, A. (2010). Model assumptions and their influence on the predicted heating load of an office building. Bauphysik, 32 (6), p.359–364.

Kim, J. M. and Clarke, J. A. (2004). The EnTrak system: supporting energy action planning via the Internet. In: Proceedings of the Congress of Tall Buildings Urban Habitats (CTBUH), 2004.

Kokogiannakis, G., Strachan, P. and Clarke, J. (2008). Comparison of the simplified methods of the ISO 13790 standard and detailed modelling programs in a regulatory context. Journal of Building Performance Simulation, 1 (4), p.209–219. [Online]. doi:10.1080/19401490802509388.

Loga, T. (2005). Nachweis, Label und Beratung der Energiepass auf dem Weg... , IWU. Darmstadt, 2005. ISBN: 3932074777 9783932074776

Loga, T., Balaras, C., Šijanec Zavrl, M., Corrado, V., Corgnati, S., Despretz, H., Roatny, C., Cyx, W., Popiolek, M., Groß, M., Georgiev, Z., Vimmr, T., Wittchen, K. B. and Kragh, J. (2010). Use of Building Typologies for Energy Performance Assessment of National Building Stocks. Existent Experiences in European Countries and Common Approach. Darmstadt, Germany: Institut Wohnen und Umwelt GmbH. [Online]. Available at: http://www.building-typology.eu/downloads/public/docs/report /TABULA_SR1.pdf [Accessed: 20 April 2012].

Loga, T., Balaras, C., Šijanec Zavrl, M., Corrado, V., Corgnati, S., Despretz, H., Roatny, C., Cyx, W., Popiolek, M., Groß, M., Georgiev, Z., Vimmr, T., Wittchen, K. B. and Kragh, J. (2012). Application of Building Typologies for Modelling the Energy Balance of the Residential Building Stock. Darmstadt, Germany: Institut Wohnen und Umwelt GmbH. [Online]. Available at: http://www.buildingtypology.eu/downloads/public/docs/report/TABULA_TR2_D8_NationalEnergyBalances.pdf [Accessed: 20 April 2012].

Loga, T., Born, R., Großklos, M. and Bially, M. (2001). Energiebilanz-Toolbox : Arbeitshilfe und Ergänzungen zum Energiepass Heizung, Warmwasser. Darmstadt: IWU. ISBN: 3932074521 9783932074523

Loga, T., Diefenbach, N. and Born, R. (2011). Deutsche Gebäudetypologie Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden. Darmstadt, Germany: Institut Wohnen und Umwelt GmbH. [Online]. Available at: http://www.building-typology.eu/downloads/public/docs/brochure/DE_TABULA_TypologyBrochure_IWU.pdf [Accessed: 20 April 2012].

Loga, T., Diefenbach, N., Knissel, J. and Born, R. (2005). Kurzverfahren Energieprofil, 04/05. Darmstadt, Germany: Institut Wohnen und Umwelt GmbH. [Online]. Available at: http://www.iwu.de/fileadmin/user_upload/dateien/energie/werkzeuge/iwu-kurzverfahren_energieprofil-endbericht.pdf [Accessed: 14 June 2012].

Loga, T., Diefenbach, N., Popiolek, M., Panek, A., Cohen, R., van Cruchter, G., Oomen, R., van Schlam, B., Corrado, V., Corgnati, S., Daskali, E., Balaras, C., Droutsa, P., Kontoyannidis, S., Gaglia, A., Cyx, W., Tomasetig, B., Devriendt, N., Maes, D., Vekemans, G., Geissler, S., Groß, M., Hofer, G., Schönauer, S., Pinggera, R., Šijanec Zavrl, M., Rakuscek, A., Panos, C., Marcos, R., Voskens, R., Hanratty, M., Sheldrick, B., Ivanov, B. and Georgiev, Z. (2009). DATAMINE Collecting Data from Energy Certification to Monitor Performance indicators for New and Existing Buildings. Darmstadt, Germany: Institut Wohnen und Umwelt GmbH. [Online]. Available at: http://www.iwu.de/fileadmin/user_upload/dateien/energie/DATAMINE_Public_Final_Report.pdf [Accessed: 23 April 2012].

Loga, T., Großklos, M. and Knissel, J. (2003). Der Einfluss des Gebäudestandards und des Nutzerverhaltens auf die Heizkosten – Konsequenzen für die verbrauchsabhängige Abrechnung – . Institut Wohnen und Umwelt GmbH. [Online]. Available at: http://www.iwu.de/fileadmin /user_upload/dateien/energie/neh_ph/IWU_Viterra__Nutzerverhalten_Heizkostenabrechnung.pdf [Accessed: 16 April 2012].

Maier, T., Krzaczek, M. and Tejchman, J. (2009). Comparison of physical performances of the ventilation systems in low-energy residential houses. Energy and Buildings, 41 (3), p.337–353. [Online]. doi:10.1016/j.enbuild.2008.10.007.

Mavrogianni, A., Davies, M., Kolokotroni, M. and Hamilton, I. (2009). A GIS-based bottom-up space heating demand model of the London domestic stock. In: Proceddings 11th International IBPSA Conference, Building Simulation, 2009.

Mullaly, C. (1998). Home energy use behaviour: a necessary component of successful local government home energy conservation (LGHEC) programs. Energy Policy, 26 (14), p.1041–1052. [Online]. doi:10.1016/S0301-4215(98)00046-9.

Natarajan, S., Padget, J. and Elliott, L. (2011). Modelling UK domestic energy and carbon emissions: an agent-based approach. Energy and Buildings, 43 (10), p.2602–2612. [Online]. doi:10.1016/j.enbuild.2011.05.013.

Neidhart, H. and Sester, M. (2006). Identifying Building Types and Building Clusters Using 3D-Laser Scanning and GIS-Data. In: 2006, Salzburg, Austria: International Society for Photogrammetry and Remote Sensing. [Online]. Available at: http://www.isprs.org/proceedings/XXXV/congress/comm4/ papers/442.pdf [Accessed: 21 June 2012].

Nielsen, T. R. (2005). Simple tool to evaluate energy demand and indoor environment in the early stages of building design. Solar Energy, 78 (1), p.73–83. [Online]. doi:10.1016/j.solener.2004.06.016.

Olonscheck, M., Holsten, A. and Kropp, J. P. (2011). Heating and cooling energy demand and related emissions of the German residential building stock under climate change. Energy Policy, 39 (9), p.4795–4806. [Online]. doi:10.1016/j.enpol.2011.06.041.

Paauw, J., Roossien, B., Aries, M. B. C. and Santin, O. G. (2009). Energy Pattern Generator; Understanding the effect of user behaviour on energy systems. In: 1st European conference energy efficiency and behaviour, 2009, p.9–10.

Page, J. (2007). Simulating occupant presence and behaviour in buildings. ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE. [Online]. Available at: http://biblion.epfl.ch/EPFL/ theses /2007/3900/EPFL_TH3900.pdf [Accessed: 10 April 2012].

Page, J., Robinson, D., Morel, N. and Scartezzini, J.-L. (2008). A generalised stochastic model for the simulation of occupant presence. Energy and Buildings, 40 (2), p.83–98. [Online]. doi:10.1016/j.enbuild.2007.01.018.

Pagliarini, G. and Rainieri, S. (2012). Restoration of the building hourly space heating and cooling loads from the monthly energy consumption. Energy and Buildings. [Online]. doi:10.1016/j.enbuild.2012.02.030.

Papakostas, K. T. and Sotiropoulos, B. A. (1997). Occupational and energy behaviour patterns in Greek residences. Energy and Buildings, 26 (2), p.207–213. [Online]. doi:10.1016/S0378-7788(97)00002-9.

Parekh, A. and Eng, P. (2005). Development of archetypes of building characteristics libraries for simplified energy use evaluation of houses. In: Proc. 9th Int IBPSA Conf, 2005, p.921–928.

Parys, W., Saelens, D. and Hens, H. (2010). Implementing realistic occupant behavior in building energy simulations–the effect on the results of an optimization of office buildings. In: Proceedings of the 10th REHVA World Congress‘ Sustainable Energy use in Buildings’, 2010, p.1–8.

Peng, C. and Wu, Z. (2008). Thermoelectricity analogy method for computing the periodic heat transfer in external building envelopes. Applied Energy, 85 (8), p.735–754. [Online]. doi:10.1016/j.apenergy.2008.02.003.

Pilkington, B., Roach, R. and Perkins, J. (2011). Relative benefits of technology and occupant behaviour in moving towards a more energy efficient, sustainable housing paradigm. Energy Policy, 39 (9), p.4962–4970. [Online]. Available at: doi:10.1016/j.enpol.2011.06.018.

Professur für Bauphysik der ETH - Bauphysik Online. (n.d.). Absorptionsvermögen a verschiedener Baumaterialien. [Online]. Available at: http://www.bph.hbt.arch.ethz.ch/Filep/ Waerme/ Waerme_Grundl/Kennwerte/emission_absorp.html [Accessed: 12 September 2012].

R Core Team. (2012). R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. [Online]. Available at: http://www.R-project.org.

Reinhart, C. F. (2004). Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. Solar Energy, 77 (1), p.15–28. [Online]. doi:10.1016/j.solener.2004.04.003.

Richardson, I., Thomson, M. and Infield, D. (2008). A high-resolution domestic building occupancy model for energy demand simulations. Energy and Buildings, 40 (8), p.1560–1566. [Online]. doi:10.1016/j.enbuild.2008.02.006.

Richardson, I., Thomson, M., Infield, D. and Cliffort, C. (2010). Domestic electricity use: A high-resolution energy demand model. Richardson, I. (ed.). Energy and Buildings, 42 (10), p.1878–1887. [Online]. doi:10.1016/j.enbuild.2010.05.023.

Robinson, D., Campbell, N., Gaiser, W., Kabel, K., Le-Mouel, A., Morel, N., Page, J., Stankovic, S. and Stone, A. (2007). SUNtool – A new modelling paradigm for simulating and optimising urban sustainability. Solar Energy, 81 (9), p.1196–1211. [Online]. doi:10.1016/j.solener.2007.06.002.

Robinson, D., Haldi, F., Kämpf, J., Leroux, P., Perez, D., Rasheed, A. and Wilke, U. (2009). CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning. In: Proc. Building Simulation, 2009.

Robinson, D., Wilke, U. and Haldi, F. (2011). Multi agent simulation of occupants’ presence and behaviour. In: Proceedings of Building Simulation, 2011.

RWI, Rheinisch-Westfäliches Institut für Wirtschaftsforschung (2011). Erstellung der Anwendungsbilanz 2008 für den Sektor Private Haushalte (Endbericht). Forschungsprojekt der Arbeitsgemeinschaft Energiebilanzen, Berlin. [Online]. Available at: http://www.ag-energiebilanzen.de/componenten/download.php?filedata=1302262886.pdf&filename=RWI_Einzelbericht_Anwendungsbilanz_Haushalte..pdf&mimetype=application/pdf [Accessed: 12 October 2012].

Rylatt, R. M., Gadsden, S. J. and Lomas, K. J. (2003). Methods of Predicting Urban Domestic Energy Demand with Reduced Datasets: A Review and a New GIS-Based Approach. Building Services Engineering Research and Technology, 24 (2), p.93–102. [Online]. doi:10.1191/0143624403bt061oa.

Saltelli, A. (2002). Sensitivity Analysis for Importance Assessment. Risk Analysis, 22 (3), p.579–590. [Online]. doi:10.1111/0272-4332.00040 [Accessed: 30 July 2012].

Saltelli, A. and Annoni, P. (2010). How to avoid a perfunctory sensitivity analysis. Environmental Modelling & Software, 25 (12), p.1508–1517. [Online]. doi:10.1016/j.envsoft.2010.04.012.

Saltelli, A., Chan, K. and Scott, E. M. (2000a). Sensitivity analysis. New York; Chichester; Weinheim [etc]: J. Wiley & sons.

Saltelli, A., Tarantola, S. and Campolongo, F. (2000b). Sensitivity Analysis as an Ingredient of Modeling. Statistical Science, 15 (4), p.377–395..

Schuler, A., Weber, C. and Fahl, U. (2000). Energy consumption for space heating of West-German households: empirical evidence, scenario projections and policy implications. Energy Policy, 28 (12), p.877–894. [Online]. doi:10.1016/S0301-4215(00)00074-4.

Schultz, J. M. and Svendsen, S. (1998). WinSim: A simple simulation program for evaluating the influence of windows on heating demand and risk of overheating. Solar Energy, 63 (4), p.251–258. [Online]. doi:10.1016/S0038-092X(98)00062-0.

Schüssler, F. (2010). Geographische Energieforschung : Strukturen und Prozesse im Spannungsfeld zwischen Ökonomie, Ökologie und sozialer Sicherheit. In: 2010, Frankfurt am Main; Berlin; Bern; Wien: Lang.

Shimoda, Y., Fujii, T., Morikawa, T. and Mizuno, M. (2004). Residential end-use energy simulation at city scale. Building and Environment, 39 (8), p.959–967. [Online]. Available at: doi:10.1016/j.buildenv.2004.01.020.

Shorrock, L. and Dunster, J. (1997). The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock. Energy Policy, 25 (12), p.1027–1037. [Online]. doi:10.1016/S0301-4215(97)00130-4.

Statistisches Bundesamt. (2012). Destatis: Statistik Wirtschaftsbereiche -Bautätigkeit -. [Online]. Available at: https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/Bauen/Bautaetigkeit /Tabellen/WohnungsbestandfrueherenBundesgebiet.html [Accessed: 5 July 2012].

StMUG, Bayerisches Staatsministerium für Umwelt und Gesundheit., StMWIVT, Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie and OBB, Oberste Baubehörde im Bayerischen Staatsministerium des Innern (2011). Leitfaden Energienutzungsplan. [Online]. Available at: http://www.stmi.bayern.de/imperia/md/content/stmi/bauen/rechtundtechnikundbauplanung/_staedtebau/veroeffentlichungen/oeko/leitfaden_enp.pdf [Accessed: 18 April 2012].

StMWIVT, Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie (2008). Bayerns ländlicher Raum (Aktuelle Informationen)-Leben und Arbeiten im ländlichen Raum-eine Dokumentation zur Lebensqualität. [Online]. Available at: http://www.stmwivt.bayern.de/fileadmin/WebDateien/Dokumente/landesentwicklung/Lebensqualitaet_im_laendlichen _Raum.pdf [Accessed: 5 July 2012].

Strzalka, A., Bogdahn, J., Coors, V. and Eicker, U. (2011). 3D City modeling for urban scale heating energy demand forecasting. HVAC&R Research, 17 (4), p.526–539..

Swan, L. G. and Ugursal, V. I. (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews, 13 (8), p.1819–1835. [Online]. doi:10.1016/j.rser.2008.09.033.

TABULA Project Team. (2012). Typology approaches for non-residential buildings in four European countries existing information, concepts and outlook. Darmstadt: IWU. ISBN: 9783941140240 3941140248

Theodoridou, I., Karteris, M., Mallinis, G., Papadopoulos, A. M. and Hegger, M. (2012). Assessment of retrofitting measures and solar systems' potential in urban areas using Geographical Information Systems: Application to a Mediterranean city. Renewable and Sustainable Energy Reviews, 16 (8), p.6239–6261. [Online]. doi:10.1016/j.rser.2012.03.075.

VDI, Verein Deutscher Ingenieure, Gesellschaft Energietechnik. (2008). Referenzlastprofile von Ein- und Mehrfamilien-häusern für den Einsatz von KWK-Anlagen. Beuth Verlag GmbH..

Wainwright, J. and Mulligan, M. (2004). Environmental modelling : finding simplicity in complexity. Chichester, West Sussex, England; Hoboken, NJ: Wiley.

Wood, G. and Newborough, M. (2003). Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. Energy and Buildings, 35 (8), p.821–841. [Online]. doi:10.1016/S0378-7788(02)00241-4.

Yao, R. and Steemers, K. (2005). A method of formulating energy load profile for domestic buildings in the UK. Energy and Buildings, 37 (6), p.663–671. [Online]. doi:10.1016/j.enbuild.2004.09.007.

Yu, Z., Fung, B. C. M., Haghighat, F., Yoshino, H. and Morofsky, E. (2011). A systematic procedure to study the influence of occupant behavior on building energy consumption. Energy and Buildings, 43 (6), p.1409–1417. [Online]. doi:10.1016/j.enbuild.2011.02.002.

Zhao, H. and Magoulès, F. (2012). A review on the prediction of building energy consumption. Renewable and Sustainable Energy Reviews, 16 (6), p.3586–3592. [Online]. doi:10.1016/j.rser.2012.02.049.