URBAN ENERGY ANALYSIS BASED ON 3D CITY MODEL FOR NATIONAL SCALE APPLICATIONS

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ABSTRACT
In this paper, we present a methodology based on 3D city model to manage a realistic energy analysis of the building stock, building per building, at a very large scale (national application for instance).

This methodology is tested on the City of Ludwigsburg and its more than 14,000 buildings. The influences of the data availability and quality on the model accuracy is analysed, for both geometrical and semantical information data. This paper is ended up by exposing some technological trends and policy needs to improve the realism and potentials of this methodology.

INTRODUCTION
Accountable for around 80\% of the oil, gas and coal world consumption, urban metropolises are the lead contributors of greenhouse gas production, a main driver of climate change, despite covering only 2\% of the Earth’s surface. A rapid transition of urban areas towards energy efficiency and adaption to challenges created by climate change are highly required.

In this context, virtual 3D city models, storing geometrical and semantic data of whole cities, have shown huge potentials in the fields City planning, Environment and Energy, from flood risk simulations to solar potential analyses (Solar Atlas Berlin, 2010). In parallel, the number of cities represented in 3D city models is skyrocketing, while the investment costs and time required to build these models are decreasing as new automatic data collection technologies such as LiDAR are developed.

Some urban energy analysis based on virtual 3D city model have already been realised at local scale for some city districts like in Berlin (Carrión et al. 2010, Kaden et al. 2013), Karlsruhe and Ludwigsburg (Nouvel et al. 2013). The data quality of these city models are very variable, depending on the available public database (provided generally by the municipality), and the information data collected on-site. Moreover, as they rely mostly on specific (non-standardised) data structures defined locally, they are not applicable to other cities and regions.

In this paper, we introduce a methodology of urban heat demand analysis which enables the calculation at national scale of the building heating demands, based on 3D city model (available in whole Germany since 2013), and on national-available databases (ALKIS database and European census data).

This methodology is first detailed and tested on the whole city of Ludwigsburg (14,000 buildings). Then, the uncertainty of the model is investigated, analysing the influence on the simulated heating demand of building information data. The influence of the CityGML Level of Details, not the same in all cities and regions, is studied as well. In a last section, we describe some technological trends and policy needs which could participate to the improvement of the realism and accuracy of this national-wide energy model.

METHODOLOGY
The urban energy analysis described and tested in this paper relies on an integrated process using a virtual 3D city model. This integrated process is implemented on the urban simulation platform SimStadt, whose development is ongoing in the Project of the same name (SimStadt, 2014).

3D city model
The OGC Standard CityGML (Groeger et al., 2012) has been selected for the modelling of 3D building data. CityGML is an open, multifunctional model which provides a basis for 3D geospatial visualization, analysing, simulation and exploration tools. In recent years, these virtual 3D city models, storing geometrical and semantical data of whole cities, have shown huge potentials in the fields City planning, Environment and Energy, and are increasingly used for it.

A considerable advantage of CityGML in comparison to other 3D city model formats is its spatio-semantic model, which specifies object modelling in different levels of detail. Due to this, it is an excellent database for heating demand analysis of existing building stocks, since the level of building parameter availability can be reflected in the Levels of Detail of CityGML (see Figure 1).
The most simple geometric representation of a building for a heating demand evaluation consists of a simple rectangular block. This block model consists of the “Level of Detail 1” (LoD1) of CityGML. The Level of Detail 2 (LoD2) adds the roof form to the building level, Level of Detail 3 (LoD3) adds in the positioning of the façade windows, and Level of Detail 4 (LoD4) incorporates the modelling of the indoor space.

The 3D city model can be generated either by stereo air photo, digital cadastre combined with building information (height, roof type) or laser scanning. In particular, the latter technique allows for an automatic generation of a CityGML model of whole cities in a short time. Since 2013, the complete building stock of Germany is modelled with CityGML – LoD1. Some regions like Saxony have already completed their 3D city model with LoD2 (Baltrusch et al. 2011).

Given the diverse qualities of the 3D city models, the healing module “CityDoctor” has been developed and integrated into the process. It allows for the control and enhancement of the geometrical quality of the 3D model by closing polygons and volumes or separating buildings with common adjacent walls (Coors et al., 2011).

Building information sources

To lead an urban energy analysis at very large scale, the two following building information sources, available in whole Germany (there may be equivalent data sets in other countries) are used:

- The Authoritative Real Estate Cadastre Information System (ALKIS®)
- The population census data

The ALKIS database is stored and managed by the Working Committee of the Surveying Authorities of the States of the Federal Republic of Germany (AdV). It contains in particular the standardised Building Function codes, related to the Building IDs of the 3D city model.

The population census occurs generally every 5 to 10 years, allowing for the collection of socio-demographic information data at national scale, by sending a survey in every household of the country. In 2011, it was even conducted at European scale. General building information, as year of construction, living/used area and number of inhabitants, are in particular included in the survey. The answer rate is generally very high for residential buildings (96% in the city of Ludwigsburg).

Although these two datasets are sufficient to simulate the heating demand of all buildings, additional databases may be provided at more local scale by the cities in order to refine the city model and improve the accuracy of the simulation results.

Data pre-processing and generation of the building simulation parameters

The relevant building information data previously described are incorporated in the 3D city model. An automatic data pre-processing module integrated in the urban platform SimStadt allows for the calculation of the required input data of the heating demand simulation, based on the available data and Level of Detail.

The boundary usage conditions (occupancy time, air change requirement, set-point temperatures etc.) are determined by relating the ALKIS Building Function codes to the standard types of building usages detailed in building energy norms (DIN 18599-10).

The building physics properties (U-values of the building elements, infiltration rate etc.) are assessed by means of benchmarking values from building typology libraries. The building typologies correspond to a classification of the whole building stock according to their building type (for instance single-family house, multi-family house, high tower or offices) and building age class. A building typology may be assigned to each building of the 3D city model, by combining its year of construction from the census data, its building function from ALKIS and some geometrical parameters extracted from the 3D building model (building height, ratio of exterior walls to adjacent walls).

Such building typology libraries are essential to address districts with several thousands of buildings. These libraries can exist at a national level (e.g. in Germany: IWU, 2003 or in the different European countries: Project Tabula, 2012), for certain regions (e.g. the states of Bavaria and Schleswig Holstein in Germany), or for specific city quarters with exemplary energy audits (e.g. Karlsruhe Rintheim). Generally, the more locally and accurately these building libraries are defined, the higher is the accuracy of the on-site construction characteristics.
Depending on the availability of additional building data sets, the values assessed first through benchmarking or standard values can be updated, particularly in regard to refurbishment measures, in order to refine the urban thermal model and improve the result accuracy.

As a result, this data pre-processing supplies formatted inputs to the heating demand calculation module.

**Heat demand calculation**

Regarding heating demand calculation, customary building performance simulation software tools are mostly not appropriate for a city-scale calculation. Namely, they require exceedingly detailed input thermal data, are not designed to use geometry input from city models, and have a programming and computation time that is much too long.

On the other hand, a purely statistical model, consisting of the multiplication of specific consumption ratios by the living area, does not benefit from the potential of 3D city modelling.

One compromise solution is the quasi-static monthly energy balance (standardised in Germany with the DIN 18599, or in Europe with the ISO 13790). This simple but reliable algorithm has been selected in this integrated process. Its limited input requirements are compatible with a 3D city model, while its robust and reasonably accurate algorithm is used worldwide by energy standard organisations (EnEV 2012 and PassivHaus in Germany, TEK 10 in Norway etc.).

Moreover, the computing time of this heating demand calculation is well suited to generate and compare long-term urban energy scenarios for districts with thousands of buildings.

From the standard DIN 18599, some simplifications and adaptations have been made. For example, every building is modelled with a single thermal zone, since their internal structure is not detailed for CityGML model LoD1 to LoD3. In the special case of multi-usage building, set-point temperatures, internal gains and air change rates have been averaged according to the respective used area. Moreover, internal gains or air change rates are fixed ratio relative to living area, depending only on the building usage and building age.

Finally, a correction factor based on empirical studies (Born et al, 2002) is integrated into the standard algorithm aiming to estimate the impact of occupant behaviour. Concretely, it directly modifies the heating set-point temperature, depending on the heat losses coefficient (and then the thermal state) of the building.

The meteorological data used for the simulation are standardised regional monthly mean irradiances per façade orientation, as well as the monthly outside dry bulb temperature (DIN V 4108-6, annex A). The calculation algorithms are implemented in the software Insel 8, coupled with the urban platform SimStadt.

**TEST ON THE CITY OF LUDWIGSBURG**

**Overview**

Ludwigsburg is a city of the South-West of Germany with nearly 90,000 inhabitants. These inhabitants live and work in more than 14,000 buildings, representing a total heated area of 5.7 million m². Ludwigsburg is administrated in 12 districts, built at different expansion periods of the city: the oldest district “Mitte” has a majority of buildings built before the 20th century, whereas the district “Pflugfelden” for instance has been built mainly after 1990.

During the project Klima SEK, a 3D city model CityGML LoD2 representing the whole city of Ludwigsburg has been built, using the laser scanning and model reconstruction technologies. The census data from the European census survey 2011 and the building functions are the only building information data sources available for the whole city (as well as for the whole of Germany) and those have been incorporated into the CityGML 3D city model.

**Simulation results**

Based on this 3D city model, the heating demand of each heated building of Ludwigsburg was simulated. In the figure 2, the results are presented on the 3D city model in kilowatt-hours per square meter (normalized by the reference heated area according to DIN 4108-2) per year. Because of data privacy reason, the heating demand of buildings composed only of one household (single-family houses and row houses) have been grouped and averaged with their neighbor buildings.

*Figure 2: Calculated specific heating demand of the city Ludwigsburg*

The simulated average specific heating demand of the buildings of Ludwigsburg is 167 kWh/m².yr, varying between 142 and 185 kWh/m².yr for the 12 different districts. The histogram of the specific heating demand for the total heated area of Ludwigsburg shows a normal distribution centered...
on 160 kWh/m²·yr, augmented by an excrecence of the category 50 – 75 kWh/m²·yr. This latter corresponds to the new constructions, built after the implementation of the building energy conservation laws (EnEV in Germany) as well as the recent building refurbishments.

**Discussion and limits of the model**

No energy consumption data were available at city scale (the different energy suppliers of Ludwigsburg keep them confidential for competition reasons). Thus, although the average heating demand calculated based on the 3D city model is coherent with the German average value of 160 kWh/m²·yr (Bine 2002), the verification and calibration of the urban energy model were unfortunately not possible.

Furthermore, the definition of the census data field “year of construction” lacks of clarity in case of refurbished buildings. Some owners of fully refurbished buildings provide the year of refurbishment and some the year of original construction. As no other refurbishment information data are considered in this urban energy model, building refurbished state were from time to time taken into account in the city modelling or not.

In general, by considering only the census and ALKIS datasets as building information data, the uncertainty of the simulated heating demand may be significant. To assess these uncertainties and verify the simulation results of this urban energy methodology, a focussed energy analysis of the district Grünbühl of Ludwigsburg is proceeded in the further section.

**INFLUENCE OF THE BUILDING INFORMATION DATA**

Beside the geometrical Level of Details, the semantic building information has a significant impact on the accuracy of the model. In the urban energy methodology previously presented for very large scale applications, only necessary building data available at national scale were included in the city model. At more local scale, additional building information may be collected to refine the city model, leading to an improvement of its result accuracy.

**Comparison of “census data model” and “detailed data model” on Ludwigsburg-Grünbühl**

Grünbühl is a small residential district in southeastern Ludwigsburg, with a ground area of 15 ha. Most of its 150 buildings were built in the decade after World War II, others later in the 80’s. During the project EnEffStadt Ludwigsburg, detailed relevant building energy data have been collected on-site (e.g. window proportion per façade, thickness of outside insulation for refurbished buildings, basement and attic configurations etc.). The 3D city model has been refined with these detailed information and simulated.

Furthermore, the only energy supplier of the district accepted to provide us with the gas consumption data of each building block for the last 5 years, which allowed us for the comparison of the simulation results with the real consumptions.

The actual heating demand calculated from the gas consumptions, the simulated heating demand based on these detailed building data and the other simulated heating demand based only on census data have been compared together for different building blocks of the district Grünbühl. The results are represented on the Figure 4.

**Figure 4: Comparison between the actual heating demand, and the two simulations based on detailed data and census data models**

The simulated data based on the census data overestimates consequently the actual heating demand (total deviation: +31%), while the simulated heating demand based on the detailed data model follow closely the actual heating demand, with a total...
deviation of 2%. In particular, the latest refurbished buildings (Building blocks 1 to 7) with the lowest specific heating demand are much more realistically modelled with all the information of the detailed data model than with the census data model.

Then, having detailed enough building information is essential to model realistically building heating demands at urban scale. The next section investigates the impact of some main energy-related building information over the calculated heating demand.

Influence of the different building information data

For the district of Grünbühl and its 150 buildings, the on-site information collection occupied 3 persons during 2 days. At larger scale (e.g. for whole Ludwigsburg), such an operation would be extremely personal- and time-consuming. Then, it is essential to know which building information data are the most relevant (and irrelevant) to collect. In other words: which information data have the strongest (and lowest) influence on the calculated heating demands, and in which specific configurations (urban form, building ages etc.).

In this section, the impact of two particular building information data over the heating demand is investigated, applied to the district Ludwigsburg-Grünbühl.

- Refurbishment data

Figure 5 shows the overestimation of the heating demand simulation when the refurbishment data are not available (case of the “census data model” compared to the “detailed data model”).

Missing refurbishment data information leads to huge errors in the estimation of the heating demand, from +70% for the first energy efficient refurbishment in the 80’s to +180% for the latest energy efficient refurbishment (and even much higher for refurbishments following the highest actual standards).

Then, having information data about the latest refurbishment state of the buildings, at least a year of refurbishment, is essential for an urban energy analysis.

- Influence of window to wall ratio

Uncertainties about window to wall ratios may lead to errors in solar gain as well as heat transmission loss calculations, and therefore, affect the heating demand. Figure 6 represents the heating demand deviation relative to the window to wall ratio error for the Grünbühl district. The considered interval of window to wall ratio corresponds to the typical range for residential buildings: 10% - 30%. For the refurbished buildings, the oldest buildings and the whole district, the heating demand deviations were calculated relative to the mean value of real window to façade ratios: respectively 17%, 18% and 20.3%.

![Figure 6: sensitivity study of the window to wall ratio](image)

In the case of Grünbühl, the uncertainty on the window to façade ratio led to a deviation smaller than +/-5% on the total heating demand and may be considered as non-key parameter for the simulation of the heating demand.

Nevertheless, this result cannot be generalized to other case studies, since it is specific to the climate (radiations and outdoor temperature), the main building orientation, and the difference between the wall and the window U-values. For instance, most old buildings of Grünbühl have new windows whose U-values are not so far from those of the walls (respectively 1.6 and 1.4 W/m².K).

INFLUENCE OF THE GEOMETRICAL LEVEL OF DETAILS

Contrary to the City of Ludwigsburg, many cities cannot afford a 3D city model Level of Detail 2 (LoD2) with detailed roof structures. A 3D city model LoD1, which is generated by combining the footprints and the average heights of the building, may be used instead for an energy analysis. Thus, the whole building stock of Germany is modelled in LoD1 since 2013.
In this section, the influence of this geometrical approximation of the 3D city model on the heating demand calculation results is quantified, by comparing the results of the heat demand calculation based on the LoD1 and on the LoD2 city models of Ludwigsburg.

The Figure 7 presents these deviations for the 12 districts of Ludwigsburg. As a general trend, the total heating demand of all districts is slightly overestimated with the LoD1 city model, in a range between 0 and 5%, with an average value of 3% for the whole City of Ludwigsburg.

This deviation is considerably correlated with the overestimation of the LoD1 reference heated area, which is calculated in function of the heated volume and of the estimated number of storeys, according to the DIN4108. The reason of this overestimation comes from the data pre-processing, which extracts the geometric data from the 3D city model and transform them in usable data for the heating demand simulation. Having the roof shape in the LoD2, it is easy to estimate if a building contains a inhabited attic storey or not, based on the distance between the ridge and the eaves height. If this distance is judged to small (less than 2 meters), the roof volume is cut off from the heated volume, and the reference building height used for the estimation of the storey number corresponds to the eaves height. In a LoD1 city model, all the roof are flat, making impossible to differentiate the heated volume from the whole building volume.

This deviation between LoD1 and LoD2 is now analysed at the building level, focussed on the district Grünbühl. Since the difference between LoD1 and LoD2 lays on the roof shape modelling, it is interesting to investigate the impact of the building height on the relative deviation of heated area and heating demand.

The Figure 8 details these deviation depending on the number of storeys of the buildings of Grünbühl. The greatest deviations corresponds to the buildings with only 3 storeys (8-10% in average), where the ratio roof volume to building volume is the highest. The deviation decreases then with the increasing number of storey down to 0-2%, except for the 11 storeys category. The latter corresponds to a high tower with a complex geometry, which should be considered as an exception.

We observe also that the correlation between the heated area and the heating demand is not exact. Indeed, additionally to the difference of calculated heated area, the various roof shape in LoD1 and LoD2 leads also to different envelope area and roof orientations, causing different transmission heat looses and solar gains, two important terms of the building energy balance..

SOME TECHNOLOGICAL TRENDS AND POLICY NEEDS

The uncertainties of this city model based on census and ALKIS datasets have been shown to be non negligible in the last sections. To improve the data quality, and therefore their realism and accuracy of the proposed methodology for very large scale applications, different solutions exists. They may come from technological fields and policy decisions.

Improvement of data collection with image mining technologies

During the last decade, the utilization of image processing technologies for urban data mining and 3D city model reconstruction have boomed, be it on street-view or aerial pictures, with visual or infra-red pictures.

Thanks to a collection of advanced image processing algorithms (image segmentation, classification methods, Markov Chain Monte Carlo, descriptive and predictive spatial models etc.), window to wall ratio (Musialski, 2010), storeys recognition, solar
panel surface area, wall absorption coefficient or the refurbishment state of the building (based on infrared camera) may be automatically determined and linked up to the correct buildings and walls by means of geo-referencing.

Furthermore, drones have become a very efficient and low-cost solution, to obtain high resolution aerial pictures and orthogonal views of façade of a whole city in a very short time.

Cloud service for crowd sourcing

To tackle energy transition at urban scale, city municipalities, energy suppliers, housing companies and private owners must be mobilized and bonded around a common long-term urban energy strategy.

It is then essential to find a place where they can communicate and exchange together, a place where top-down policies meet bottom-up enterprises. This place may be the web, the support: a cloud GIS (Ramesh et al. 2013). GIS allows for merging large amounts of data and cartography into a single map which serves exchange support and decision making tool. Its “cloud” feature (online) allows for making it accessible by every urban actors for crowd sourcing, while managing the different “access perimeters” depending on the user type.

Through web-based services, building owners and tenants may for instance feed the city model with energy-related information concerning their building, and get as feed-back a customised calculation of the energy saving potential due to some refurbishment measures and the relative investment costs. Construction and refurbishment companies may identify the highest refurbishment requirements in the city and propose a cost estimations to the owners. Energy supplier companies may feed the model with their energy billing data, and investigate the profitability of a new District Heating System, given as the actual heat intensity of an urban area.

Then, every urban actors will get an incentive to provide the cloud GIS with detailed energy-related data, participating in the data quality improvement of the city model and then to its higher accuracy and realism.

Introduction of energy-related data in the population census survey

Some of the socio-demographic information data collected during the national/European population census are essential for an urban energy analysis (year of construction, building function, number of inhabitants), but often not enough to get an accurate energy characterization of the city building stock. The inclusion in the census survey of energy-related information data, like type of HVAC systems, last year of refurbishment, building insulation etc., would be very effective in order to take realistically into account the energy state of the national building stock.

Data privacy versus energy refurbishment urgency

Energy billing data at disaggregated level (for instance per building) are precious information, allowing for calibration through reconciliation of a the model’s predicted energy consumption with actual consumption. Indeed, since standard calculation methods, as the DIN 18599 in Germany or ISO 13790 in Europa, determine the intrinsic heat demand of one building with standardised occupants, without encompassing the household type or the occupants’ behaviour, they may deviate considerably from the actual consumption.

Unfortunately, the access to these consumption data tends to be still restricted in some countries for privacy or marketing reasons. This is particularly paradoxal in Germany, while the federal government is fully involved in a energy-efficiency upgrade of the national building stocks, which require to know which buildings must be refurbished, in which priorities, and what are the energy saving potentials.

The question of consumption data privacy deserves to be asked. Why yearly energy consumption data should remain private, while energy performance audits (“Energieausweis” in Germany) become mandatory for every buildings? Couldn’t be beneficial to compare its own consumption with neighbors’, to be more aware about its consumption? Couldn’t be beneficial to communicate its own consumption to its municipality, to get some information about refurbishment possibilities, and participate to the planning of a low-carbon urban policy? For the energy suppliers, couldn’t it be beneficial to know the energy demand of all the buildings of a district, to plan a profitable district heating system?

CONCLUSION

In this paper, we introduce a methodology of urban heat demand analysis which relies only on national-available 3D city model and building/occupants databases (ALKIS database and European census data). Tested first on the whole city of Ludwigsburg, the next stage would be the calculation of the heating demand of each building of Germany, residential or not. This methodology could be even extended to other regions/countries, on condition that they have at disposal a 3D city data model and a cadastral database with standardised building functions.

The uncertainties of this model have been proved sizeable, some great opportunities of data quality improvement exist. They may come from technological fields (image processing, web platforms) or policy decisions (enhancement of the European census data with energy-related
information, publication of the energy consumption data).

In any case, 3D city models have the potential to lead the energy transition national-wide. Beside the thermal diagnosis of the existing building stock, they enable also to develop and plan a complete urban energy strategy, with the localization of energy saving potentials and the definition of refurbishment priorities, so as to fulfill, in combination with sustainable energy supplying concepts, the CO2 saving objective of the German department of energy and environment: carbon neutral District in 2050.

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