Urban Energy Computing: a Multi-Layered Approach

Ardeshir Mahdavi[1], Stefan Glawischnig[2], Neda Ghiassi[3]

Abstract: Smart urban-level applications require high-fidelity and high-resolution models. This circumstance has raised the interest in computational models of mass, energy, and information flows in the urban context. Toward this end, we focus in the present contribution on a multi-layered approach to urban energy computing. The variance in the spatial and temporal resolution of the queries' purpose and informational background suggests that different computational approaches may be deemed appropriate. Our modelling approach involves thus three strategies, addressing *i)* bulk informational requirements regarding large segments of an urban context, *ii)* queries requiring an overall understanding of the dynamic nature of building blocks' energy performance, and *iii)* a detailed urban energy computing level involving massive computing.

Keywords: smart cities, urban energy computing

1 Introduction and Background

Smart urban-level applications require high-fidelity and high-resolution models. This circumstance has raised the interest in computational models of mass, energy, and information flows in the urban context. Toward this end, we focus in the present contribution on a multi-layered approach to "urban energy computing". With this term, we mean the computational assessment of urban-level energy production, distribution, and transformation processes. Such processes include multiple urban sectors and domains (buildings, transportation, industrial production, etc.). However, we focus here on the urban-scale building stock. The importance of buildings as the dominant urban energy sink is well understood [EU10]. A few common use cases for urban energy computing are as follows: *i)* the prediction of energy efficiency implications of district-level thermal retrofit measurements, *ii)* the assessment of the potential of promotion and incentivisation of the installation of building-integrated renewable energy harvesting systems (e.g. solar-thermal collectors, photovoltaic panels), and *iii)* provision of support for the configuration and real-time operation of energy production, transportation, and storage components of smart grid systems. These instances shed light on the general impetus behind the proposed multi-layered approach to urban energy computing, namely the heterogeneous nature of urban-scale energy-related inquiries: The variance in the spatial and temporal resolution of the queries' purpose and informational background

[1] TU Vienna, Department of Building Science and Building Ecology, No. 13, Karlsplatz, 1040, Vienna, Austria, amahdavi@tuwien.ac.at
[2] stefan.glawischnig@tuwien.ac.at
[3] neda.ghiassi@tuwien.ac.at

suggests that different computational approaches may be deemed appropriate. Accordingly, our modelling approach involves the following three layers of computational strategies:

- The first approach address bulk informational requirements pertaining to large segments of an urban context. In this scenario, high level performance information must be obtained in an expedient, efficient, and possibly automated manner. For this purpose, we have developed computational methods to extract from 2-dimensional urban GIS resources the necessary geometric and semantic information for energy calculations of whole building blocks. The information thus obtained is processed and interpreted such that it could be provided to pertinent – typically steady-state – energy calculation routines (see section 2).
- For queries requiring an overall understanding of the dynamic nature of building blocks' energy performance, a (cluster) sampling method has been developed and tested. Thereby, representative instances of a given urban fabric are identified and subjected to detailed transient thermal analysis. The results are subsequently up-scaled to the underlying population, thus providing support for urban-level applications pertaining, for example, to smart energy grids (see section 3).
- Ongoing work targets a third detailed urban energy computing level, whereby, existing and projected buildings are dynamically and comprehensively represented in terms of real and virtual sensors/meters respectively. The platform is intended to obtain real-time information from smart metering infrastructure and combine those with simulation-based virtual sensors representing projected buildings and assorted future scenarios such as urban-level retrofit projects (see section 4).

The contribution explains the specific strengths of each layer and their complementary nature in addressing a wide range of energy-related urban-scale queries toward provision of timely decision support for a variety of relevant agents and stakeholders.

2 Bulk building energy use estimations at urban district scale

Recently, we developed a systematic framework for the assessment of urban microclimatic conditions [Ki15]. Various geometric properties and topological relationships, which are derived from open GIS-data are used to calculate microclimatic attributes for representative areas in the city of Vienna. European Union generally mandates the implementation of open data interfaces. In 2007, the Directive 2007/2/EC of the European Parliament and of the Council [EU07] established an infrastructure for Spatial Information exchange in the European Community [EU15]. The methods introduced here utilize this standard and the defined data interfaces. Based on two-dimensional vector data, high-resolution raster data and point-wise attributive information available via open government data channels, methods are implemented to automatically calculate sky view factor, aspect ratio, pervious and impervious surfaces, built surface fraction, etc. [Gl14]. Building on this method and the idea to utilize existing spatial data, the two-dimensional GIS-data is utilized to automatically generate three-dimensional, topological building models that offer the necessary input information to calculate steady-state energy demands for entire building blocks.

Buildings are initially derived from cadastre data that is combined with attributive data, such as (i) building area, (ii) perimeter, (iii) relative building height, (iv) height above digital elevation models, (v) number of storeys, and (vi) construction period. Currently, the building model is stored in a graph database and can be distributed as JSON and XML. It consists of three entities: (i) Building, (ii) Storey, and (iii) Element. Buildings consist of various storeys. Depending on the storey type and the construction period, basic physical properties, such as heat transmission coefficients are determined. Each storey has multiple wall elements that are currently either directly exposed to the outdoor climate or non-exposed (e.g. fire walls). An analysis of the storeys and the surrounding/neighbouring buildings allows determining the orientation of the element, the type (external or partition walls) and the shading.

The proposed building model is created in four steps. Every building needs a geometry representing the building footprint. First, the type of geometry is determined and tested for topological correctness. The semantic building properties are calculated and/or imported (gross/net area, perimeter, building id, relative building height, number of building storeys, height above see level, building type and year of construction). Depending on the geographic location and the height above sea level, the default climate settings are determined. After the building and all of its properties are successfully mapped, the details of the building model (storeys and elements) are generated based on the geometry and base attributes. After the determination of a topologically correct two-dimensional building footprint, the building is brought to the third dimension. With the creation of the basic building entity from GIS data, basic geometric, physical, and meteorological properties can then be used to derive building storeys. Based on the building storeys, wall elements are generated. The geographic building models are stored in a graph database. This allows high-performance access, which is necessary to estimate bulk building energy uses on district level. The geographic building models can be used as three-dimensional entities or as single-zone thermal models to support simulation.

Upon the creation of building models from GIS-data, a lightweight method to estimate energy demands was implemented using ISO 13790:2008 [Is12]. The national implementation of the European framework for energy certificates [EU10] for Austria [Oe14] is used to create a lightweight mathematical model. Due to the two-dimensional nature of the available GIS-data and the lack of certain attributes (e.g., wall materials, retrofit documentation, roof geometries, etc.), the standard's model is simplified to handle GIS-based input data and is implemented in a JavaScript framework). Applying the procedure to a set of approximately 900 buildings in the city centre of Vienna showed promising results. Specifically, buildings with a homogenous, non-complex building footprint and geometry are imported and processed correctly with minor deviations from manually calculated standard energy certificates.

3 Cluster Sampling for Simulation-based Urban Energy Modelling

Planning and management of small scale distributed power/heat generation plants, deployment of smart or responsive grid concepts, and creation of grid-independent urban clusters require energy demand information with high temporal resolution. On the other hand, realistic representation of occupant behaviour, boundary conditions, and technological aspects of buildings are crucial for detailed investigation of implications of change scenarios for the energy use patterns of building agglomerations. Dynamic building performance simulation (BPS) tools can approximate building energy demand with high temporal resolution and incorporate various climatic, behavioural, and technological aspects. But the extensive informational and computational requirements of these applications hamper their direct incorporation in large scale energy inquiries. Sampling methods help reduce the spatial scope of the required computations to a manageable size, and thus facilitate using BPS tools for urban energy computing. In most previous attempts at building sampling or archetyping, buildings are classified according to form/size (as a representation of building geometry), construction or refurbishment year (as an indicator of the thermal quality of building components), and usage (as an expression of operational parameters). Contextual parameters such as adjacency relations and orientation of building components, as well as the shading effect of the surrounding buildings are often ignored, despite the significance of these parameters for the energy performance of buildings in the context of cities with diverse morphological layouts, such as organically developed European or oriental cities.

The developed solution involves the implementation of Multivariate Cluster Analysis, (MCA) methods [Ha10] on a matrix of energy-relevant building parameters, automatically derived from available large-scale data sources including official and crowd sourced GIS information ([Vi15], [Os15]) as well as building standards [Oe14]. In the present implementation, MCA identifies groups of buildings with similar energy-relevant characteristics. The variables adopted to represent buildings are: *Effective average envelope U-value* (weighted by respective buildings' components), *Effective window to wall ratio* (corrected for orientation, shading and g-value), *Thermal compactness* (ratio of heated volume to thermally effective envelope), *Heated volume*, *Effective floor height*, *Daily area-based internal gains*, *Daily air change rate*, and *Ratio of daytime use hours to total use hours* (representing the temporal dynamic of building operation). Once building clusters are identified, sample buildings are selected as representatives of clusters and subjected to dynamic performance simulation. Simulation results are then up-scaled based on the developed clustering schema to obtain an overview of the energy behavior of the investigated neighborhood. Data acquisition, processing and analyses, as well as the selection of samples are automatically carried out through an open-source GIS environment [Qg15], with the help of a plug-in specially developed for the purpose. The plug-in, developed in Python [Py15] and incorporating some packages of the R Project for Statistical Computing [R15], supports three well-known MCA methods and includes algorithms to identify the most appropriate number of clusters. Once finalized, the plug-in will be released on the QGIS plug-in portal.

4 Dynamic real and virtual urban-level energy flow processes

The previous discussion elaborated on methods to *i)* obtain values of aggregate energy indicators suitable for high-level benchmarking scenarios and *ii)* conduct statistically representative analyses of the dynamic thermal behaviour of whole urban districts. Given a number of pertinent contemporary trends (rise in computational power and the spread of urban-scale smart metering and environmental monitoring campaigns), we expect that a further increase in the spatio-temporal resolution and inclusivity of urban energy computing applications is both possible. Consequently, platforms are expected to emerge that would facilitate the real-time representation and visualisation of urban-level energy production, transportation, storage, and transformation processes. Even though a detailed treatment of such a platform is not possible here, a number of relevant technologies and methods should be briefly mentioned. Specifically, we focus on dynamic numeric co-simulation techniques supported by scalable monitoring infrastructures [Za15].

Advanced numeric co-simulation provides the possibility to dynamically adjust the discrete time-domain intervals of numeric heat transfer computation. Thus, instead of bulk pre-processed data sources on boundary microclimatic conditions (e.g. test reference weather files) and internal processes (e.g. standard diversity profiles), the simulation engine can be supplied with real-time monitored data, improving the realism of the modelled processes. Real-time boundary microclimatic conditions can be obtained either from the available public and private meteorological station networks or emulated via downscaling of meso-scale climatic data into microclimatic data via techniques such as computational fluid dynamics. Internal boundary conditions (pertaining to user presence and energy-relevant behaviour in buildings), on the other hand, can be either inferred from smart metering networks via data mining, or derived from stochastic treatment (calibrated randomisation) of bulk information on diversity profiles [TM15]. These technologies have provided the necessary conditions for the implementation of hybrid urban energy monitoring platforms that fruitfully combine data from real sensors and meters (for outdoor and indoor climate as well as electrical and thermal energy flows) as well as virtual ones (supplied with data from co-simulation processes involving building fabric, building systems, external boundary conditions, and internal processes).

5 Concluding Remarks

We introduced a multi-layered approach to urban energy computing. Efficient derivation of bulk energy estimated for urban neighbourhoods can be already achieved via automated extraction of building model data from GIS sources and through application of well-established steady-state calculation methods. More recently, we have demonstrated that the dynamics of energy transfer processes can be captured for relatively large urban segments via application of cluster sampling techniques coupled with detailed time-domain building simulation. The ongoing work points to the next level of informational and temporal resolution based on platforms that capture and visualise detailed urban energy flow process via hybridisation of real and virtual sensor/meter information powered by both physical infrastructures and co-simulation platforms. The proposed multi-layered approach to urban energy computing arguably bears the potential to effectively address a broad spectrum of queries pertaining to the prediction and modulation of essential city-level energy flows.

References

[EU07] EU, Directive 2007/2/EC of the European Parliament and of the Council, Official Journal of the European Union. 2007.

[EU10] EU, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, Official Journal L 153. 2010.

[EU15] EU, The European parliament and the council of the European union, INSPIRE, http://inspire.ec.europa.eu, cit. 18.12.2015.

[Gh15] Ghiassi, N. et al.: An Enhanced Sampling-based Approach to Urban Energy Modelling. Proc. of 14th IBPSA Conf. IBPSA, Hyderabad, 2015.

[Gl14] Glawischnig, S. et al.: A case study of geometry-based automated calculation of microclimatic attributes. Taylor and Francis, 2014.

[Ha10] Hair, J.F. et al.: Multivariate Data Analysis - a Global Perspective. Pearson Global Editions, New Jersey, 2010.

[Is12] International Organization for Standardization: Energy performance of buildings -- Calculation of energy use for space heating and cooling. ISO. 2012

[Ki15] Kiesel, K.: The influence of the urban microclimate on the thermal performance of buildings. Phd Thesis, Technical University of Vienna, Department of Building Physics and Building Ecology. 2015.

[Ma13] Mahdavi, A. et al.: A framework for the evaluation of urban heat island mitigation measures. Fraunhofer IRB Verlag, 1/1/1. 2013.

[Os15] Open Street Map, www.openstreetmap.org, cit. 18.11.2015.

[Oe14] OENORM B 8110: Thermal insulation in building construction, Austrian Standards Institute, Vienna, 2014.

[Py15] Python, www.python.org, cit. 18.11.2015.

[Qg15] QGIS, www.qgis.org, cit. 18.11.2015.

[R15] R Project for Statistical Computing, www.r-project.org, cit. 18.11.2015.

[TM15] Tahmasebi, F., Mahdavi, A.: Stochastic models of occupants' presence in the context building system control, Advances in Building Energy Research, 1, 2015.

[Vi15] Vienna GIS, www.wien.gv.at/viennagis, cit. 18.11.2015.

[Za15] Zach, R. et al.: A distributed and scalable Approach to Building Monitoring, Journal of Information Technology in Construction, 20 (Special Issue), 2015.