High-resolution representations of internal and external boundary conditions in urban energy modelling

Ardeshir Mahdavi, Neda Ghiassi, Milena Vuckovic,
Mahnameh Taheri, Farhang Tahmasebi
TU Wien, Vienna, Austria

Abstract

Integrative computational environments that can support effective planning of urban-level energy management activities are indispensable to the development of sustainable cities. These environments rely on urban energy models, which, bound to achieve computational efficiency, have in the past frequently relied on simplified procedures. However, the temporal dynamics of load patterns and their dependency on transient phenomena (e.g., inhabitants' presence and actions) cannot be realistically represented when using simplified models. To address this circumstance, we have conceived the framework of an integrative urban decision support environment, relying on simulation. In this regard, we have designed, implemented, and documented an urban energy modelling approach that combines cluster analysis and sampling techniques to enable full dynamic numeric simulation capability. The latter capability enables in principle the processing of highly resolved time series data pertaining both to external (microclimatic) and internal (user-dependent) boundary conditions. In this paper, we elaborate on the framework of the envisaged environment, introduce its various components, and report on our current developmental activities.

Introduction

In recent years, the interest in the development of urban-scale decision support environments has been steadily increasing. This is in part due to the insight that certain critical questions regarding energy and environmental performance of the built environment cannot be sufficiently treated at the level of individual buildings. Such integrative environments rely on an urban energy model to compute the energy performance of the investigated domain. However, bound to achieve some measure of computational efficiency, urban-scale modelling efforts frequently rely on various domain simplifications. For instance, heat transfer phenomena are captured using reduced order models. This could involve not only the simplification of the geometry and zonal complexity of modelled buildings, but also a significant reduction of the temporal resolution of the modelling results. As a consequence, certain important queries cannot be accommodated with appropriate levels of resolution. Specifically, the temporal dynamics of load patterns and their dependency on transient phenomena (e.g., weather conditions, inhabitants' presence and actions) cannot be realistically represented. Moreover, conventional computational tools and routines for the generation and maintenance of the initial and subsequent versions of the urban information model require a high degree of manual user intervention, rendering such tools and routines less effectual.

To address these circumstances, we have conceived the framework of an urban decision support environment, which supports the high-resolution representation of various energy-influential aspects of the urban building stock, and simulation-supported assessment of stock energy performance in view of various change and intervention scenarios. These scenarios may pertain to demographic and behavioural changes, macro and micro-level climate change, physical, infrastructural, and technological interventions, etc. To facilitate this, we have implemented an urban energy modelling approach that combines cluster analysis and sampling techniques with full dynamic numeric simulation capability. The latter capability enables in principle the processing of highly resolved time series data pertaining both to external (microclimatic) and internal (user-dependent) boundary conditions. The envisaged environment couples various developments in the fields of microclimate modelling and occupancy modelling to represent the internal and external boundary conditions of the urban building stock with appropriate detail. In this paper, we introduce the intended computational environment and report on the recent developments of the project.

Background

Urban energy modelling

Over the past years, a wide variety of energy models has been developed for the assessment of the energy performance of large assemblies of buildings. These models vary significantly in overall approach, underlying computational methods, informational requirements, and temporal and spatial resolution of the results. Bottom-up engineering models (Swan and Ugursal 2009), are generally considered the most appropriate for the investigation of various change and intervention scenarios (Kavgic et al. 2010). This is due to their independence from historical data and reliance on heat transfer principles to assess the performance of a number of individual buildings representing an urban

https://doi.org/10.26868/25222708.2017.019

area and extrapolate the results to the entire domain. Reductive stock representation, commonly achieved through building stock segmentation and sampling or archetyping, aims to minimize the effort and information required to assess the performance of all buildings in the domain. Given the upsurge in computational power and speed over the past years, provision of the required input data is considered as the most effort intensive activity towards performance assessment. Former efforts have frequently relied on segmentation schemas based on buildings' construction periods, built form and principle usage. However, especially in the case of historical buildings, which constitute a major part of the European building stock, constant retrofit and densification interventions render the efficiency of construction period to represent the thermal quality of a building questionable. Usage can be a reliable indicator of the operational characteristics of a building, however, in multi-usage buildings, it is not always trivial to decide which usage dominates the operational tendencies of the building. Contribution of contextual parameters, such as the adjacency relations and the effect of mutual shading in reducing the solar gains, to the performance diversity in the urban building stock is almost unanimously ignored in the former efforts. For a more extensive review of former building stock classification schemes see Ghiassi et al. (2015).

Despite implementation of sampling and archetyping procedures, most former efforts still depend on steady state and reduced order performance computational methods, which fail to cater for queries pertaining to the design and development of innovative supply-side energy management strategies such as distributed generation and energy autonomous neighbourhoods. For such investigations energy demand data with high temporal and spatial resolution is required. Moreover, regardless of the efficiency of the implemented reductive procedure, loss of diversity is an inherent consequence of reductive efforts. This can lead to seemingly negligible misrepresentations of the dynamic load patterns, which may in fact have significant implications for the design and deployment of new energy paradigms.

Occupant Representation

Many methods and models have been developed for the representation of occupants' presence and actions for building performance assessment purposes. These include schedule-based, rule-based, and stochastic occupancy models (Yan et al. 2015), which are meant to cater for the requirements of various types of building-level energy inquiries. However, fewer efforts have addressed the issue of detailed representation of occupants for urban-level investigations. These efforts frequently rely on time-use survey data to define typologies of occupants, which offers a solid empirical basis but limits the scope of application (e.g., Shimoda et al. 2003, Baetens and Saelens 2015). Munoz and Peters (2014) have explored the potential of utilizing neighbourhood level census data to generate statistically accurate occupant populations and distribute them among buildings to achieve a more realistic representation of the diversity of occupants. More recently, special attention has been paid to agent-based occupancy modelling (e.g. Langevin et al. 2015) due to its potential to not only represent people's presence and actions but also emulate their tendencies and decision mechanisms.

Urban Microclimate

With recent advances in technology, an increasing number of comprehensive tools for generation of external boundary conditions for building thermal performance models are becoming available. In general, global circulation models (GCMs), regional weather forecasting models, and computation fluid dynamics (CFD) models have been widely applied to generate time-domain urban microclimatic information (Wilby and Wigley 1997, Memon et al. 2008, Mirzaei and Haghighat 2010). However, the coarse resolution climate data generated with global and regional models, as well as the time-intensive nature of preparation and execution of such models together with the necessary high level of knowledge, expertise, and experience for properly conducting simulations and interpreting the results, impose major challenges for their application in building energy assessments.

Recently, an alternative approach to generate location-dependent urban weather information was proposed by Bueno et al. (2012). They developed a meteorological modelling software, named urban weather generator (UWG) that derives from meteorological parameters in existing rural weather files corresponding weather representations for locations within the urban fabric. UWG considers a large number of initial parameters that vary from building material thermal properties (e.g., albedo, emissivity, conductivity, U-value for glazing) and building characteristics (e.g., internal heat gain, infiltration, ventilation), to the urban and reference rural site morphology (e.g., façade to site ratio, vegetation coverage). However, a number of these parameters are at times not readily available, thus being often subjected to approximations. Hence, the uncertainties associated with assumptions related to the input parameters, especially related to the buildings and their physical, contextual, and operational properties may have major implications for resulting model-driven weather information.

Approach

The intended urban decision support environment is targeted at the assessment and comparative analysis of the energy and emission implications of a wide range of scenarios pertaining to the following aspects:

- Physical interventions: Thermal retrofit, densification, etc.
- Technological and infrastructural interventions: Integration of distributed generation systems, efficient heating systems, etc.
- Climatic changes: Urban Heat Island Studies, etc.

- Occupant behaviour changes: Induced by demographic changes, lifestyle changes, etc.

The environment is composed of several modelling components which cater for the representation of physical and technological aspects of buildings, as well as internal and external boundary conditions of the investigation domain with appropriate resolution. A simulation-supported computational engine at the core of this environment incorporates the generated representations towards high-resolution assessment of the performance of the neighbourhood. The overall structure of the intended environment is displayed in Figure 1.

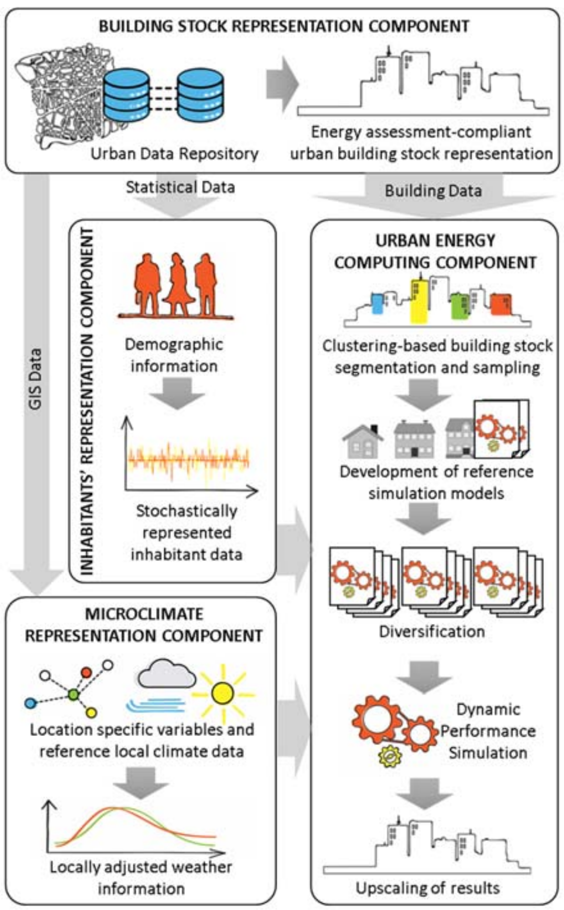

Figure 1: The overall structure of the simulation-supported urban decision support environment

The following components are considered in the currently ongoing implementation:

1. Building stock representation component
2. Microclimate modelling component
3. Occupancy modelling component
4. Simulation-based energy computing component

To facilitate data transfer, user interaction, and visualization of the results, the environment is integrated with Geographical Information Systems (GIS). Due to the adopted modular system architecture, it can be enhanced with additional functionalities such as economic analysis models and energy generation potential assessment procedures in the future. The following sections of the paper provide further details on the above-mentioned system components.

Building Stock Representation Component

This component incorporates the data available at large scale to generate an energy relevant representation of the urban stock. For this purpose, available large scale data including official GIS data, (i.e., land use plans, digital surface and elevation models, and georeferenced building inventory data), crowd-sourced web-based GIS data (i.e., GoogleMaps 2016, Open Street Maps 2016), relevant standards and guidelines (pertaining to the definition of operational building characteristics and thermal quality of the envelope) can be utilized.

In an attempt to explore the potentials and the challenges of this approach, the authors have developed a data analysis routine, deployed as a plug-in for an open-source GIS environment, which processes the available GIS data as well as pertinent standards to develop energy-relevant representations of the buildings within an urban domain. The developed routine extracts the area, orientation as well as adjacency relations of various building components. Applying a simple rule-based logic, it determines the shape of the roof and the condition of the attic space. Based on the average ratio of window to wall, the area and orientation of the glazed building components are determined. The effect of mutual shading is approximated for each glazed facade using the corresponding Sky View Factor. Further on, the process utilizes the information on the construction period of the building to determine the thermal properties of various building components. The official building inventory data is used to identify the main usage of the building. This information is enriched by the data contained in Open Street Map (2016). Following a simple logic, the volume of the building is distributed among the various usages existing in the building. Finally, operational parameters associated with these functions are extracted from the relevant standards. This leads to the generation of an energy-relevant representation of the urban building stock. Figure 2 depicts the current underlying building data representation of this component. However, in view of the recent advancements in the development of standard energy-compliant urban data representation schemas (Benner et al. 2016), their adoption for the representation and storage of urban stock models is intended in future developmental activities. The current implementation has been developed for the Austrian context but can be readjusted for other geographical contexts with minor modifications.

For more information on the stock representation component see (Ghiassi and Mahdavi 2016a, Glawischnig 2016).

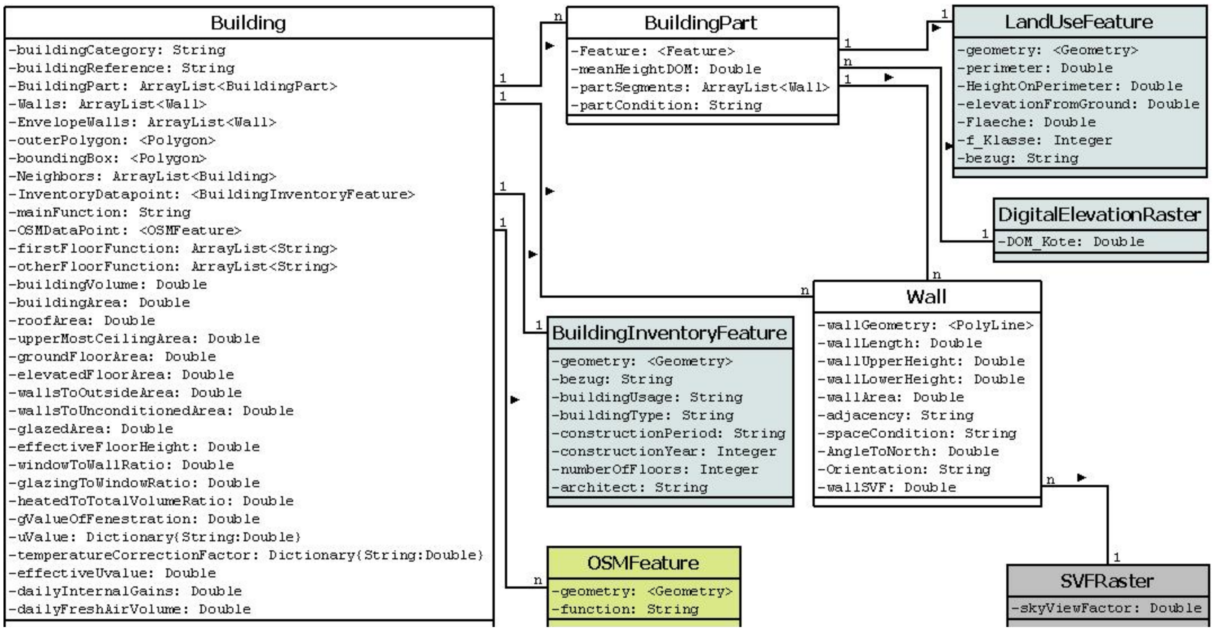

Figure 2: The underlying building data representation schema of the building stock representation component

Representation of inhabitants

Although several research efforts have addressed the issue of occupancy modelling at urban scale, most have relied on an ad hoc description of the aspects of the occupants' behaviour, which must be included in the urban-level representations. Presently, there is no well-documented guideline on how to represent occupant related aspects in large assemblies of buildings. Even at building level there appears to be no consensus among experts on which models to implement for various types of queries (Mahdavi and Tahmasebi, 2016). At urban level, in addition to the issues pertaining to the representation of the primary processes pertaining to occupants' presence and actions, additional factors must be considered. These include, amongst other things, socio-economical characteristics of the inhabitants, which influence their tendencies, preferences, and decisions. Thus, scenarios pertaining to behavioural changes for instance through demographic changes, or induced by various monetary instruments or educational campaigns, can be assessed.

Towards this end, the present project follows two parallel developments. The first development addresses the fundamental lack of a framework for the representation of occupants. In this regard, the development of an ontological structure involving the various influential aspects of occupant behaviour is undertaken. Initial steps for this developmental activity have been taken in a former project on the representation of monitored data (Mahdavi and Taheri 2016). The current development, however, focuses exclusively on occupants and their appropriate representation at various levels of resolution and for different types of energy-related inquiries. Once this ontology is generated, an appropriate modelling method can be conceived to support the development of various scenarios with regard to occupants.

In the meantime, to fulfil the data requirements of the presented urban decision support environment, a simple method has been adopted to provide a stochastic representation of occupant behaviour based on reference schedules suggested by standards (e.g., ASHRAE 2013). These schedules capture the occupancy related aspects at an aggregate level, however, their application for large-scale assessments may result in unrealistically monotonous load profiles.

Previous studies suggest that in the probability distributions of certain aspects of occupants' behaviour (e.g., arrival time in office spaces) the Coefficient of Variance displays a relatively stable value range (Mahdavi and Tahmasebi 2015). Based on this observation, for every time step of the occupancy related schedules a Gaussian probability distribution was generated based on the corresponding value of the reference schedule (as the mean of this distribution) and a default CV value of 0.2. The generated schedules feature similar tendencies to those of the reference schedules. However, they enable a more realistic representation of the diversity of the inhabitants at large scale.

Preliminary simulation runs suggest that the employment of these schedules only slightly modifies the overall annual energy demand predictions. To investigate the impact of the stochastic method on simulation results, for a number of buildings with various usages (residential, office, and mixed use residential and commercial) simulation models were developed using reference schedules. Then, permutations of the reference simulation models with stochastically generated schedules were generated. The results of these models were compared to those of the reference model. The adopted reference schedule and a sample of a stochastically generated set of schedules (for 5 days) are compared in Figure 3. The generated schedules share the general characteristics of the reference schedules. The results of a hundred simulation runs of a typical Viennese residential building with various schedules were compared to the reference schedule-based assessments. The EnergyPlus (2016) simulation software was used for the assessments.

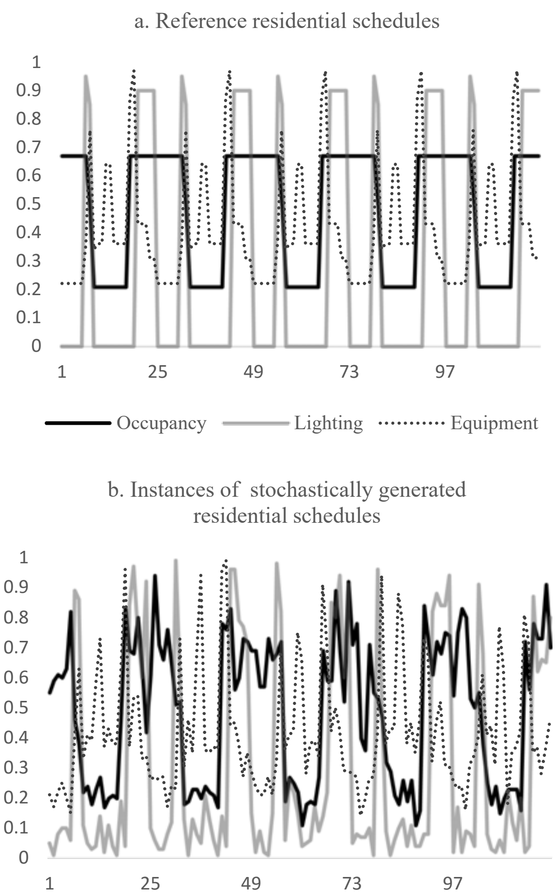

Figure 3: a. Reference schedules for a residential building, b. Example of stochastically generated schedules for a building for 5 days

Figure 4 illustrates the range as well as the average values of relative deviations of the hourly heating demand predicted by the models with stochastic occupant representation from the outcome of the reference model. The plotted results pertain to a week in the heating season. As seen in this graph, the predicted hourly demand values can deviate by as much as 20% from the reference schedule-based assessments. The average demand across the hundred models for every time step however, remains within ±3% of the reference values.

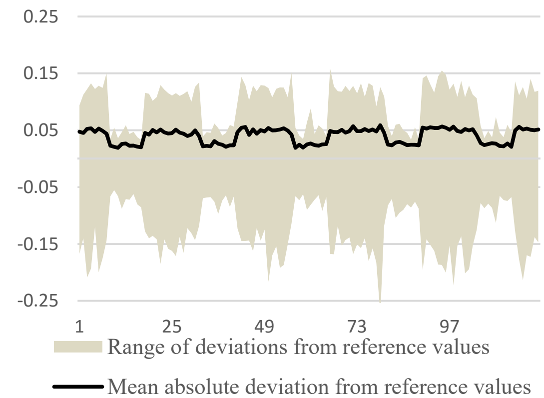

Figure 4: Relative deviation of the hourly heating demand values from the reference model predictions, due to stochastic representation of occupants.

The stochastic inhabitant representation procedure is currently integrated in the computational component of the environment. To improve the performance of this model, future research includes the demographically-based definition of typologies for occupants (based on Munoz and Peters 2014), as well as integration of more advanced techniques with regard to stochastic modelling and diversification schemes.

Representation of microclimatic variance

Identification of independent variables

In previous research efforts, we explored the extent and the implications of microclimatic variation in the city of Vienna (Kiesel et al. 2013, 2016a, 2016b). For this purpose, local microclimatic conditions from a distinct set of high-density and low-density urban areas in Vienna, referred to as the Urban Units of Observations (U2O), were investigated. The results suggested that local climatic context can vary considerably depending on the site features, such as morphological and physical urban attributes, referred to as the U2O variables. For instance, we could establish a significant correlation between the local urban heat island intensity and a number of location-dependent geometric, morphological, and semantic variables, including, sky view factor, height-to-width ratio of street canyons, impervious surface fraction, built surface fraction, effective mean building compactness, surface albedo, emissivity, and anthropogenic heat emission (Mahdavi et al. 2013, Vuckovic et al. 2016). Figures 5, 6, and 7 illustrate some of the observed correlations in the context of Cumulative Temperature Increase (CTI), a novel measure of "overheating", for the same set of urban areas in Vienna, Austria (Mahdavi et al. 2016). In general, certain urban features (aspect ratio, built area fraction, equivalent building height, effective mean compactness) are hypothesised to positively correlate with CTI, whereas others (sky view factor, unbuilt area fraction, pervious surface fraction, albedo) are more likely to display a negative correlation.

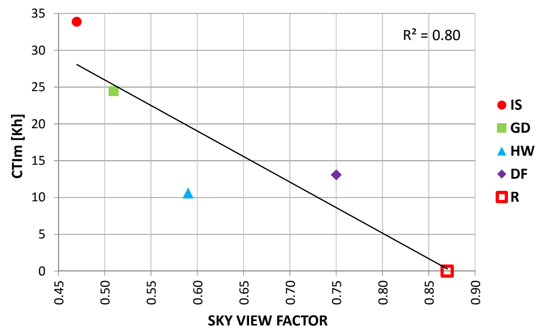

Figure 5: CTI as a function of sky view factor.

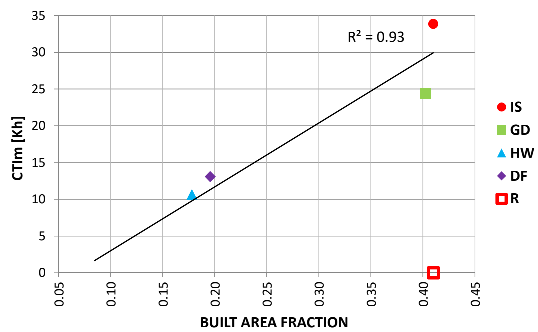

Figure 6: CTI as a function of built area fraction.

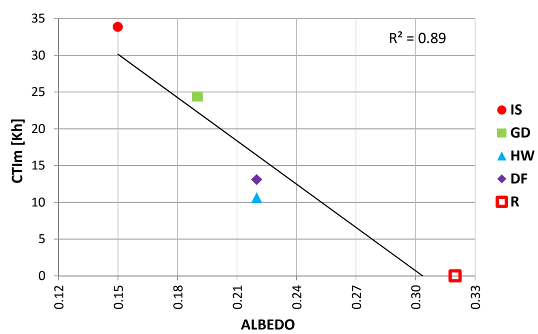

Figure 7: CTI as a function of albedo.

Aspects of generative procedures for high-resolution locally adjusted urban microclimate models

Given the aforementioned foundations, the proposed research shall outline a path to advance techniques toward local weather data generation. Specifically, we hypothesise that distinct microclimatic conditions in a specific urban setting can be reliably derived from microclimatic conditions within a non-urban setting, based on pertinent differentials in U2O values. The reasoning behind the selection of a non-urban domain for the analysis is as follows: Building design support applications (specifically energy performance simulation tools) are typically provided with climatic data generated from reference weather stations, which are certified (amongst other things, based on regular standardised calibration measures) to provide reliable information and act thus as the source of data for all downstream applications. While not essential for our approach, these stations are typically located in the proximity of airports. Consequently, it is practical to derive inner-city microclimatic conditions from such reference (often rural or suburban) stations.

To facilitate the respective developmental work, the following stepwise procedure is envisioned: In a first step, high-resolution meteorological information, pertaining to air temperature, relative humidity, global solar radiation, wind speed, and precipitation, is collected from an operational non-urban weather station. The collected information is further processed to derive 12 monthly-geared hourly-based reference days. This will allow for the comprehensive analysis of the main prevailing monthly climatic tendencies. Subsequently, corresponding values of the U2O variables are derived for this domain. Advance data extraction routines incorporated into Geographic Information Systems (GIS) functionality, as introduced by Glawischnig et al. (2014a, 2014b), are deployed for this purpose. Specifically, a set of algorithms was engineered within a Python-based framework, and further used for the quantitative analysis of location-dependent U2O attributes. In a second step, sample urban domains are selected and corresponding U2O variables derived. Additionally, high-resolution meteorological information is obtained for these domains.

One important aspect of further inquiry is to investigate how the non-urban weather data matrix changes in relation to changes introduced in U2O variables. To do so, the computed U2O parameters are analysed in the context of respective deviations between urban and non-urban domains. Thereby, the degree of variance from the reference non-urban U2O value is computed and respective implications for the meteorological parameters investigated. This inquiry is supported by well-established statistical methods, such as the multivariate regression techniques, in order to explore the aggregate correlations between meteorological parameters and U2O variables.

The multivariate analysis of time-dependent relationships between reference and local weather data leads to a statistically significant transformation coefficients matrix. These multivariate dependencies can explain the diurnal distribution and monthly variations of local meteorological parameters. They thus yield a distinct set of temporal transformation coefficients to transform each of the meteorological parameters in a reference (e.g., non-urban) weather data matrix. To represent these dependencies in a high-resolution and realistic (stochastic) manner, statistical randomisation techniques are employed. Thereby, at every time-step (i.e., for each hour) the coefficient matrices are randomly manipulated (using, potentially, Monte Carlo techniques as alluded to by Wilks and Wilby 1997) and deployed to map the non-urban weather data matrix onto the local urban one. For this purpose, we plan to investigate the potential of different probability distribution functions of a given meteorological parameter to specify the variation of stochastically generated variables. This component is meant to preserve the physically realistic temporal (diurnal) sequence of the meteorological time-series.

Once transformed, the non-urban weather time-series may be evaluated and calibrated against the empirically obtained meteorological information from urban domains.

The resulting methodology is expected to support the generation of dynamic and highly realistic locally-adjusted microclimate boundary conditions toward more reliable simulation-based urban energy and environmental assessments. This will allow, among other things, for systematic impact analyses of envisioned mitigation measures (as realised in terms of increase or decrease in relevant U2O values).

Urban Energy Computing Method

Overview

The developed urban energy computing method follows an engineering bottom-up modelling approach with full-fledged dynamic simulation capabilities. This computational framework is consisted of two modules. The reductive module is tasked with the systematic reduction of the computational domain through stock segmentation and sampling. The second module attempts at partial recovery of the diversity lost through the reductive process to facilitate more realistic representation of the energy behaviour of the investigated domain.

Reductive module

Similar to former reductive procedures, this module relies on a segmentation and sampling method to reduce the modelling space. However, instead of relying on vague indicators such as construction period, it utilises the building stock representation developed by the first component to computationally determine the values of a set of descriptive indicators, reflecting the various energetically relevant aspects of the buildings.

Moreover, this module employs Multi-variate cluster analysis (Hair et al. 2010) techniques to identify groups of buildings with similar energy behaviour. This technique allows for the incorporations of a larger number of criteria in the classification or segmentation process, with control over the number of the emerging classes. Also, since this method does not rely on specific location-dependent information for the identification of clusters, its adoption renders the computation engine generic and therefore applicable to various geographical contexts, so long as the stock representation component is adapted for that context. Once the cluster analysis is performed, buildings with the most typical characteristics across each cluster are selected to represent it.

In order to identify the most appropriate set of descriptive indicators as clustering criteria, as well as the most efficient clustering algorithms, several scenarios were conceived and deployed. The performance of the scenarios towards effective reduction of the computational domain while reliably representing the overall energy traits of the neighbourhood was assessed using a simplified heating demand calculation method (standard). For this purpose, the heating demand of all buildings in the study domain was computed based on the generated stock representation. Then the volume related demands of the representative buildings emerging from each reductive scenario were used to extrapolate the demand of the entire domain. The aggregated neighbourhood level results as well as the building level deviations were compared.

The descriptive indicators involved in the scenarios are listed in Table 1. Each scenario included a subset of these indicators such that all operational, physical, and contextual parameters of the building were involved. Three cluster analysis algorithms were examined for stock segmentation: K-means clustering (MacQueen 1967), Hierarchical agglomerative clustering (Hair et al. 2010) and model-based clustering (Fraley and Raftery 2002). The k-means method with the set of indicators highlighted in the table proved to perform best in predicting the aggregated and building-level demand of the case study (with an aggregate error of less than 1% and an average building level error of 12%). For more information on the details of the implemented methods see Ghiassi et al. 2015, and Ghiassi and Mahdavi 2016b.

Re-diversification Module

Once the representative buildings are selected, detailed simulation models can be generated for these buildings. As mentioned before, all reductive efforts inevitably diminish the diversity of the urban building stock in their representation. Although this loss of diversity may not affect the energy assessment reliability of the model at large scale, it may affect the predicted energy implications of various change and intervention scenarios. This is due to the fact that even though buildings in the same class may have similar thermal performance, they may respond differently to a certain improvement intervention. To partially capture this variation, the re-diversification process generates a unique simulation file associated with every building in the study domain. Then it utilizes the values of several descriptive indicators pertaining to the building computed in the previous step, to manipulate the non-geometric features of the pertinent simulation model, to better emulate the energy behaviour of the represented building. The building features currently subjected to diversification are reference values for the area-related number of occupants, equipment and lighting power, air change rate, and thermal properties of the main components of the building envelope (upper most and lowermost enclosures of the conditioned envelope as well as external walls). The descriptive indicators that inform the diversification process are the area-related daily internal gains and air change rate, and the effective U-values of the building components. The average internal gains value is disaggregated to occupant-related, equipment, and lighting gains. The reference equipment and lighting values as well as the number of the occupants is determined such that the overall gains match the value suggested by the indicator. A similar logic is employed to compute the hourly air-change rate.

Table 1: List of descriptive indicators considered as criteria for building stock classification through Multivariate Cluster Analysis. The highlighted indicator performed best in view of representation of heating demand

	Abbr.	Variable	Description/ comments	Data sources
Geometry	V_n	Net Volume (m^3)	An indicator of the size of the building	Vienna GIS 2015 ÖNORM 2014
	A_e	Thermally effective envelope area (m)	Area of the heat emitting envelope corrected for adjacency relations	
	h_e	Effective floor height (m)	Ratio of the building volume to the floor area determined by the footprint geometry and the number of floors	
	C_t	Thermal compactness (m)	Ratio of the net building volume to the thermally effective envelope area	
Solar gains	GR_e	Effective glazing ratio	Average glazing to wall ratio weighted by orientation and corrected for the shading effect of the surroundings represented by the Sky View Factor. Weights associated with orientations were based on reference climate data	Vienna GIS 2015 Hammerberg 2014 ÖNORM B 2014
Thermal Quality	U_e	Effective average envelope U-value ($W.m^{-2}.K$)	Average u-value of the envelope corrected for adjacency relations and weighted by the corresponding areas	Vienna GIS 2015 OIB 2015
	U_{we}	Effective Wall U-value ($W.m^{-2}.K$)	Average u-value of wall elements corrected for adjacency relations and weighted by the corresponding areas	
	U_{ce}	Effective Roof/Ceiling U-value ($W.m^{-2}.K^{-1}$)	Average u-value of roof/ceiling elements corrected for adjacency relations and weighted by the corresponding areas	
	U_{we}	Effective Floor U-value ($W.m^{-2}.K^{-1}$)	Average u-value of floor elements corrected for adjacency relations and weighted by the corresponding areas	
Operational Parameters	O_u	Annual use fraction	Fraction of time the building is used over a year	Vienna GIS 2015 ÖNORM 2011 Open Street Map 2016
	$O_{d/u}$	Daytime use intensity	Ratio of the daytime use hours to total use hours	
	O_d	Daytime use fraction	Fraction of year the building is used during daytime	
	O_n	Nighttime use fraction	Fraction of year the building is used during nighttime	
	$q_{i,h}$	Average area related internal gains rate ($W.m^{-2}$)	Average rate of internal gains per unit of floor area weighted by the share of every usage of the total area	
	Ig_d	Daily area related internal gains ($Wh.m^{-2}.d^{-1}$)	Daily internal heat gains per unit of area during the heating season, determined by the area-related internal gains and daily use hours	
	n_v	Average hourly air-change rate (h^{-1})	Average air-change rate weighted by the share of every usage of the total volume of the buildnig	
	Ac_d	Daily air-change rate (d^{-1})	Daily air-change rate determined based on daily use hours and hourly airchange rate	

The effective U-values of building components are weighted by the share of the relevant components in the building's thermal envelope. As such, they are not only dependent on the construction of the component but also on the geometry of the building and its adjacency relations. Since the diversified models share the geometry of the pertinent representative building, any deviations in the effective u-values of the components have to be accounted for through modification of the thermal properties of the components of the new model. This is achieved through a manipulation of the conductivity of the most thermally effective layer of the diversified constructions, such that the overall values of the indicators are obtained. For each building, the volume-related energy profile of the associated diversified model is used to compute the demand.

Preliminary results show that the diversification process does not significantly modify the predictions of the non-diversified model, thereby not compromising the integrity of the model. However, at building level it can result in as much as 20% deviation in the annual volume-related heating demand. This deviation can be even more significant, when observing the hourly demand values. This diversity is expected to improve the predictive accuracy of the model. Its performance however, needs further evaluations. The future research in this regard, also involves exploring the potential of geometric readjustments.

Conclusion

The present contribution reported on the research and developmental efforts towards generation of a modular simulation-supported integrative urban decision support environment. In this regards various modules of the envisaged framework, pertaining to the representation of microclimate conditions, occupant behaviour, and the physical and morphological aspects of the building stock, as well as the computational engine of the environment were introduced.

Thereby, the respective fundamental research and implementation work highlight the critical relevance of a number of insights gained. First, the underlying computational engine for the urban modelling environment must incorporate dynamic numeric simulation capability. The proposed and implemented urban energy computing approach provides an efficient solution for this requirement. Second, the full exploitation of this capability requires commensurately high-resolution and diversity-oriented representations of both external (microclimatic) and internal (occupancy-driven) boundary conditions. The respective initial implementations of these two models as presented in this paper have shown to be highly promising. The overall urban energy modelling environment thus is expected to meet the necessary conditions for accommodating complex queries regarding the implications of climatic and demographic aspects of urban development scenarios.

Acknowledgements

The authors would like to acknowledge the support of Ulrich Pont, Kristina Kiesel, and Stefan Glawischnig towards the research project presented in this paper.

References

ASHRAE Standard 90.1. (2013). Energy Standard for Buildings Except Low-Rise Residential Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. U.S. Department of Energy. Atlanta. USA.

Baetens, R., and D. Saelens (2015). Modelling uncertainty in district energy simulations by stochastic residential occupant behaviour. *Journal of Building Performance Simulation 1493*, 1–17.

Benner, J., Geiger, A., Häfele. K.H. (2016). Virtual 3D City Model Support for Energy Demand Simulations on City Level - The CityGML Energy Extension. Proceedings of REAL CORP Conference, Hamburg, Germany, 777-786.

Bueno, B., Norford, L., Hidalgo, J., Pigeon, G. (2012). The urban weather generator. *Journal of Building Performance Simulation 6 (4)*, 1-13.

Energy Plus. (2016). www.energyplus.net

Fraley, C. and E. Raftery (2002). Model-based clustering, discriminant analysis, and density estimation. *Journal of the American statistical association 97(458)*, 281-297.

Ghiassi, N., and A. Mahdavi (2016a). Utilization of GIS data for urban-scale energy inquiries: a sampling approach. Proceedings of the 11th European Conference on Product and Process Modelling. Limassol, Cyprus.

Ghiassi, N., and A. Mahdavi (2016b). A GIS-based framework for semi-automated urban-scale energy simulation. Proceedings of the Central Europe towards Sustainable Building 2016. P. Hàjek, J. Tywoniak, A. Lupisek (ed.); issued by: CESB2016; Eigenverlag der CESB2016, Prague, Czech Republic, 2016, ISBN: 9788027102488, 161 – 162.

Ghiassi, N., Hammerberg, K., Taheri, M., Pont, U., Sunanta, O., Mahdavi, A. (2015). An enhanced sampling-based approach to urban energy modelling. Proceedings of BS2015, 14th Conference of International Building Performance Simulation Association, Hyderabad.

Glawischnig, S. (2016). An urban monitoring system for large-scale building energy assessment. Dissertation. Department of building physics and building ecology, Faculty of architecture, TU Vienna. Vienna, Austria.

Glawischnig, S., Hammerberg, K., Vuckovic, M., Kiesel, K., Mahdavi, A. (2014b). A case study of geometry-based automated calculation of microclimatic attributes. 10th European Conference on Product and Process Modelling, Vienna, Austria.

Glawischnig, S., Kiesel, K., Mahdavi, A. (2014a). Feasibility analysis of open-government data for the automated calculation of the micro-climatic attributes of Urban Units of Observation in the city of Vienna. Proceedings of the 2nd ICAUD International Conference in Architecture and Urban Design, Epoka University, Tirana, Albania.

GoogleMaps. (2016). www.google.at/maps

Hair, J.F., Black, W.C., Babin, B.J., Anderson, R.E. (2010). Multivariate Data Analysis – a Global Perspective. Pearson Global Editions, New Jersey, USA.

Hammerberg, K. (2014). DEMTools. QGIS plugins repository. https://plugins.qgis.org/plugins/DEMTools

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., Djurovic-Petrovic, M. (2010). A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment 45(7)*,1683–1697.

Kiesel, K., Vuckovic, M., Mahdavi, A. (2013). Representation of weather conditions in building performance simulation: a case study of microclimatic variance in Central Europe. 13th Conference of International Building Performance Simulation Association, Chambéry, France.

Kiesel, K., Vuckovic, M., Mahdavi, A. (2016a). The scope and implications of the urban microclimate variance: a case study. CLIMA 2016, Proceedings of the 12th REHVA World Congress, Aalborg, Denmark.

Kiesel, K., Vuckovic, M., Mahdavi, A. (2016b). Exploring the implications of variance in urban microclimate for buildings' energy performance: a simulation based approach. BauSIM 2016, Dresden, Germany.

Langevin J., Wen J., Gurian, P.L. (2015). Simulating the human-building interaction: Development and validation of an agent-based model of office occupant behaviors, *Building and Environment 88*, 27–45.

MacQueen, J. (1967). Some methods for classification and analysis of multivariate observations. Proceedings of the 5th Berkeley symposium on mathematical statistics and probability. University of California Press, Berkeley, USA.

Mahdavi, A. and M. Taheri (2016). An ontology for building monitoring, Journal of Building Performance Simulation.

Mahdavi, A. and F. Tahmasebi (2015). The inter-individual variance of the defining markers of occupancy patterns in office buildings: a case study, Proceedings of BS2015, 14th Conference of International Building Performance Simulation Association, Hyderabad, 2243–2247.

Mahdavi, A. and F. Tahmasebi 2016. The deployment-dependence of occupancy-related models in building performance simulation. *Energy and Buildings 117*, 313–320.

Mahdavi, A., Kiesel, K., Vuckovic, M. 2013. A framework for the evaluation of urban heat island mitigation measures, sb13 munich, Implementing Sustainability - Barriers and Chances, München, Deutschland.

Mahdavi, A., Kiesel, K., Vuckovic, M. 2016. Methodologies for UHI Analysis. In: Counteracting Urban Heat Island Effects in a Global Climate Change Scenario; Musco, F., Ed.; Publisher: Springer, 2016; pp. 71-91.

Memon, R.A., Leung, D.Y.C., Liu, C.H. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences 20 (1)*, 120-128.

Mirzaei, P.A. and F. Haghighat (2010). Approaches to study Urban Heat Island – Abilities and limitations. *Building and Environment 45*, 2192-2201.

Munoz H.E., and I. Peters (2014). Constructing an Urban Microsimulation Model to Assess the Influence of Demographics on Heat Consumption. *International Journal of Microsimulation 7*, 127–157.

OIB. 2015. RL-6: Energy behavior of buildings. Austrian Institute of Construction Technology, Vienna Austria.

ÖNORM. 2011. B 8110-5 Thermal insulation in building construction, Part5: Model of climate and user profiles. Austrian Standards Institute, Vienna, Austria.

ÖNORM. 2014. B 8110-6 Thermal insulation in building construction, Part6: Principles of verification methods – Heating demand and cooling demand – National application, national specifications and national supplements to ÖNORM EN ISO 13790. Austrian Standards Institute, Vienna, Austria.

Open Street Map. (2016). www.openstreetmap.org

Shimoda, Y., Fujii, T., Morikawa, T., Mizuno, M. (2003). Development of Residential Energy End-Use Simulation Model at City Scale. Proceedings of the 8th IBPSA Conference, Eindhoven, Netherlands, 1201–1208.

Swan, L. G., 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)*, 1819–1835.

Vienna GIS. (2015). www.wien.gv.at

Vuckovic, M., Kiesel, K., Mahdavi, A. (2016). Toward advanced representations of the urban microclimate in building performance simulation. *Sustainable Cities and Society 27*, 356–366.

Wilby, R.L. and T.M.L. Wigley (1997). Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography 21(4)*, 530-548.

Wilks, D.S. and R.L. Wilby (1997). The weather generation game: a review of stochastic weather models. *Progress in Physical Geography 23(3)*, 329–357.

Yan D., W. O'Brien, T. Hong, X. Feng, H.B. Gunay, F. Tahmasebi & A. Mahdavi (2015). Occupant behavior modeling for building performance simulation: Current state and future challenges. *Energy and Buildings 107*, 264-278.