Developing teaching in urban building energy modelling
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Jane Doe[1], Richard Roe[2], John Stiles[2]
[1]Institution 1, City 1, Country 1
[2]Institution 2, City 2, Country 2

(The names and affiliations SHOULD NOT be included in the draft submitted for review)
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Abstract

Urban Building Energy Models (UBEMs) are increasingly important tools for national and local authorities seeking to understand and manage their carbon emissions. As such tools move from the preserve of research into the more general application, interest in learning about their application is increasing. The quantity of data inherent in a UBEM and its complexity, means that educating students in the underpinning principles and their application requires teaching a wide body of knowledge. This presents significant challenges for educators required to fit within predefined limits for teaching courses. The authors have now taught urban-scale building energy modelling to 3 cohorts of students in India, Peru and the UK using two different approaches. This paper summarises the contents of the courses and the approach taken to delivering the required learning in the limited time available. It details student feedback, outcomes and lessons learned for the different approaches and the challenges which remain.

Highlights

- The first publication on efforts to deliver education on urban building energy modelling
- Results of teaching initiatives on three continents are presented
- Three key challenges for UBEM education are identified
- The importance of using real examples with personal relevance for students is highlighted

Introduction

The World Green Building Council estimates that globally buildings are currently responsible for 39% of global energy-related carbon emissions: 28% from operational emissions, from the energy needed to heat, cool and power them, and the remaining 11% from materials and construction (World Green Building Council, 2019). In light of the climate emergency, there is an urgent need to transition cities to more sustainable environments by improving building energy efficiency. As Hong et al. (2020) highlight: urban energy analysis is a complex, multi-scale, multi-sector challenge which demands a new breed of tools to support the rapid pace of decision making, which is vitally needed.

Urban building energy models (UBEMs) are numerical simulations of the performance of groups of buildings, usually co-located. UBEMs aim to assess the aggregated dynamics of the group of buildings and, to differing extents, to take account of the effects each building has on its surroundings. Langevin et al. (2020) classify UBEMs according to whether they are top down or bottom up and the extent to which calculations are based on underlying physical models or statistical models (white box vs. black box models). While both top-down statistical and bottom-up black box models have been used extensively in assessment of national and international scale energy use metrics, they are limited by both the availability of historic data and their inability to account for changes in the underlying physical processes from which statistical models were derived (Kavcic, 2010).

There are two distinct categories of building physics-based models:

1. Those which have been developed from tools used for modelling individual buildings which incorporate detailed multi-zonal models and full dynamic thermal simulation

2. Those which have been developed expressly for urban modelling purposes in which a focus on computational efficiency has driven the use of reduced order models such as RC models in which each building is typically represented as a single thermal zone (Ferrando et al., 2020).

Urban building energy modelling is a fast-developing field and future developments are likely to focus on coupling and multi-domain simulation models which include buildings, district energy systems, urban micro-climate, transportation, and electricity transmission networks to effectively model complex urban systems. Automatic integration of city data is another key development strand (Hong et al., 2020).

The scale which UBEMs aim to cover and the wide range of data needed to characterise a city's building stock mean that urban building energy modelling is a complex, multi-disciplinary field in which a compromise must be achieved between the detail of representation, model accuracy, usability, data quality, and computational effort (Robinson et al., 2009). An important consequence of this is the need for a new class of professionals with the technical modelling skills to harness the ever-increasing availability of city data and the judgement and understanding needed to deal with its complexities.

Aims of this paper

In response to this increasing demand for urban building energy modelling skills, the authors have sought to develop a programme of education in urban building energy modelling, which is described in the rest of this article. The paper begins by considering existing approaches to education in building performance simulation and how they can be related to UBEMs, before describing the education programme which has been developed and implemented in three very different universities around the world, in both semester and block week formats. The outcomes and lessons learned from each iteration are considered and recommendations are made for future development, both for this programme and for those which might be developed by other educators in future.

Urban building energy modelling education

A literature review was undertaken to understand previous research on urban building energy simulation. The search was undertaken in the Scopus database using the search string TITLE-ABS-KEY (("Building Performance Simulation" OR "UBEM" OR "Urban building energy modelling" OR "Urban Energy Modelling" OR "building stock modelling" OR "BSM") AND ("education" OR "pedagogy" OR "teaching")). The initial search resulted in 97 records and was then refined by restricting the search to journals dealing with energy, computing science or the built environment and articles published in English resulting in 53 records of which 27 related to building performance simulation education. A manual review of the abstracts revealed that no research has previously been published on UBEM education.

In contrast, a body of literature exists on the subject of teaching-building performance simulation, although as Clarke (2015) notes, it represents a disparate range of approaches. Alsaadani and Bleil de Souza (2019) undertook a review of this literature focusing on Building Performance Simulation (BPS) teaching initiatives at undergraduate and postgraduate levels in architectural education. They identified three distinct paradigms for such initiatives - training experts, training producers of BPS and training consumers of BPS, focusing on the anticipated focus of the students in future. Other authors, for example, Reinhart et al. (2015) have discussed an alternative approach where the end goal is not to teach BPS for its own sake but rather to use it as a tool in the teaching of building science. Within this framework, the training initiatives described in this article are focused on developing students as producers of simulation.

A key concern of educators has been the danger that increasing the user-friendliness of simulation tools does "not alter the difficulty of understanding the complex thermo-physical processes and interactions within building and environmental control systems" (Hand and Crawley, 1997) and the need for simulationists to understand the underlying physical processes they are modelling and how they are simplified and represented in the model. Beausoleil-Morrison and Hopfe (2016) echo this concern, noting that while it is relatively easy to train users to generate simulation results, even for experienced users it is difficult to produce accurate results and that users often place too much faith in their simulation tools, observing that the user is often the greatest source of uncertainty. To address this Beausoleil-Morrison and Hopfe (2015) propose implementing a continuous learning cycle in which theory and simulation tools are introduced in tandem and structured exercises follow the delivery of concrete information with results reviewed in a process termed "simulation autopsy" in each lecture cycle. The cycle is illustrated in figure 1.

Since UBEM is based on the same principles as BPS, the challenge of training students in the critical evaluation of simulation results as well in the processes required to produce those results is at the heart of the question. However, it is compounded by the complexity of the data on which simulation is based. Ang et al. (2020) identify 5 key steps in UBEM workflows:

1. Data pre-processing - sourcing and processing necessary data and filling gaps
2. Model generation - compiling data and urban geometry model into a 'simulation ready' state.
3. Simulation - generate load profiles, indoor temperature and energy use
4. Calibration - harmonise simulation output with measured data
5. Application - using the resulting UBEM to support end use goals and objectives.

One of the most critical differences between urban scale simulation and work on individual buildings is in the scope of the first two steps. While pre-processed cityGML models are available for some cities, these are in the minority and developing a UBEM for most contexts will require consolidating and processing of input data. These steps often involve combining data sets collected for such varied purposes as levy-

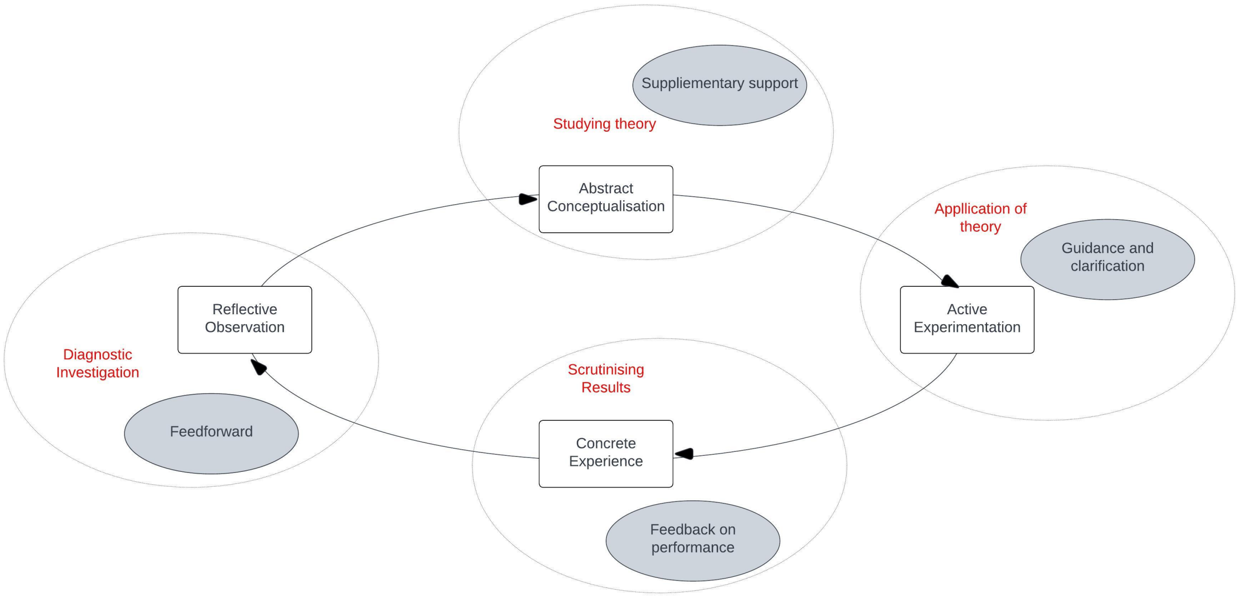

Figure 1: Beausoleil-Morrison and Hopfe's continuous learning cycle based on Kolb's experiential learning theory

ing property taxes, energy certification and land use planning. Linking these datasets and extracting the information of interest for the simulation requires an understanding of their structure, contents, strengths and weaknesses, all aspects which need to be incorporated within UBEM education

We summarise then that there are 3 key challenges that need to be addressed in UBEM education:

- The need for a sound understanding of underlying building physics concepts
- Acquisition of the skills required to access, process and critically assess input data
- The ability to critically assess outputs

While these challenges apply also to BPS education, the key difference between this and existing educational approaches is the type of input data which is available - particularly the reliance on urban data sets collected for a wide range of non-energy related purposes. This article sets out how the authors have developed and implemented UBEM training at undergraduate and postgraduate levels and the evolution in methods and content over time.

Methods

The authors are academics at institutions in the UK, India and Perú and the training programmes have been adapted to fit within existing curriculum frameworks at each institution. In each case, the training provided was a credit-bearing, optional component of an existing degree programme. Fitting within existing institutional frameworks dictated the time available and the format in which courses could be taught, while the programmes within which the training initiatives were situated dictated the existing skills and experience of students, as well as the learning objectives for each initiative. Student backgrounds varied across architecture, engineering and urban planning. The case studies used in the training were based on the locality in which the training was delivered which had important implications for the availability of data in each case. The context and format of each initiative are summarised in table 1. In each location, teaching was delivered collaboratively by academics from a mix of partners.

Pedagogical approaches

Pedagogical approaches were similar at all three institutions with a focus on research-based learning and experiential learning in line with the model proposed by Beausoleil-Morrison and Kopfe (2015). Since the focus of the training initiatives in each case was for students to apply new knowledge and skills to real-world problems, collaborative learning approaches were at the heart of the delivery methods (Kuh, 2012). In Ahmedabad and Lima, where an intensive format was used, students were allocated at random into groups which worked together throughout the teaching and learning process to develop a group responsible for a specific part of the study area which had been allocated to their group. In Lima and Ahmedabad, assessment was focused on group work. In London, where assessment focused on individual work, groups varied between sessions. But in each setting collaborative learning was a key feature. Sessions were structured in 4 stages reflecting the experiential learning cycle model shown in figure 1.

- Studying theory - students were asked to prepare for sessions by reading assigned texts, conducting web searches or watching short videos which introduced theoretical concepts in advance of classroom sessions. In class, sessions began with reflections from students on the pre-readings before

Table 1: Content and format of training initiatives

Context	**India**	**Perú**	**UK**
Time	Dec 2019	Sept 2022	Jan - Mar 2023
Course format	Block week	Hybrid	10 unit module
Student cohort	MSc and final year undergraduates	2nd & 4th year undergraduates	MSc
Teaching team mix	Ahmedabad, London	Lima, Ahmedabad, London	London, Ahmedabad
Previous experience	Either GIS or BPS experience	GIS experience	Building Physics, some BPS experience
Assessment	Mix of group work and individual assignment	Broader Individual assignment assessed at end of term	Individual assessment
Course aims	develop skills in building energy models for individual buildings and understand how to use python to automate the production of energy models for groups of buildings	understand thermal comfort and energy consumption in buildings, develop building energy modelling skills, apply building energy modelling to understand thermal comfort in a low-income neighbourhood in Lima	be able to analyse large urban data in order to derive input data for building energy models, be able to apply Geospatial Information Systems to explore and visualise urban energy data, develop urban building energy model to explore decarbonisation strategies.

formalising the concepts and relating them to the learning objectives for the specific session. The theory studied varied in each setting according to students' prior experience and knowledge, with a stronger focus on geospatial analysis in London and Ahmedabad in contrast to Lima where building physics received relatively more focus.

- Applying theory - students worked in groups to apply the theory, as well as enabling peer support, discussion was encouraged as students reviewed the theory which had been studied and decided how to implement it. For example in Lima, thermal comfort was a key output metric which needed to be related to building simulation in a manner which was new to students. Following the introduction of the concepts, students undertook a short exercise to explore perceptions of thermal comfort amongst their group before discussing results and clarifying misunderstandings. In London, model validation was a focus for the final session of the module and following the presentation of the theory, students undertook an exercise to evaluate model results using simple metrics for accuracy working together to adjust outputs to calibrate their model.
- Scrutinising results - each group reported back on their results and the teaching team led a constructive discussion on the results and how they could be interpreted and developed in future. In London where the assessment was based on individual projects, students were encouraged to report on their progress each week from the mid-point of the term, sharing results of data processing and model assembly with the class and receiving feedback from teaching staff on their work.
- Reflective observation was encouraged through the class discussions of each group's results. Group work was structured to encourage reflection for example in London, group exercises focused on comparing and contrasting results produced by different members of the group.

The focus on group work supported the experiential learning approach during the active experimentation and reflective observation phases in particular, supporting the students as active participants in the knowledge creation process rather than passive recipients of theory.

Input data

A fundamental challenge of UBEM is collecting, processing and linking data collected for a range of purposes to create an input data model for the simulation tool. The input data model comprises information about

- Building Geometry
- Building fabric
- Ventilation and air-tightness
- HVAC systems and controls
- Internal gains (equipment, lights, people)
- Occupancy schedules
- External Weather

This information needs to be extracted from a range of urban data sets, collected for diverse purposes such as taxation (information on the use and floor area), certification (information on building fabric, plant and equipment), flood risk management (information on geometry from LiDAR mapping) etc. Linking data is a key challenge since data collected for different purposes may not have a single consistent unit of reference. Moving from the individual building to the urban scale brings a need for automatic processing of the large volumes of data needed to characterise the geometry, building fabric, occupancy and loads in a large number of buildings. The need to characterise location, geometry and interfaces with other buildings means that urban-scale building energy modelling is intrinsically a geospatial challenge. For students in London, where a wide range of data was available, developing geospatial analysis skills to enable data cleaning, processing and developing methods for dealing with missing data, formed the focus of the early weeks of the teaching initiative. In Lima where no urban data sets were available, the focus was different - students worked in groups to manually extract building data from satellite imagery before visiting site to deepen their understanding, collect data on building fabric and validate assumptions. In Ahmedabad, a GIS survey of buildings was available providing data on building footprints. However, data on building heights/number of storeys was not available, nor was data on building uses. To address this, students undertook site visits to understand building uses and validate other data. In each setting, students were encouraged to reflect on the challenges of describing complex urban environments and the impact that these difficulties would have on simulation outputs.

Modelling tool

The tool chosen for the teaching initiatives was SimStock (Claude et al., 2019), a python based modelling platform which uses EnergyPlus (Crawley et al., 2001) as the core simulation engine. SimStock fits the first category of UBEM tool described by Ferrando et al. (2020) having been derived from tools for individual building modelling. The ability to create multizonal models was particularly important for assessing the diverse range of uses within a single building in Ahmedabad and enabled a floor-by-floor analysis of thermal comfort in Lima. In the SimStock model workflow the input data are pre-processed to extract building geometries and semantic details then the IDF files are generated for each building with context buildings as shading objects. The IDF files are then batch simulated in EnergyPlus using a python script. The SimStock tool was chosen because it was platform independent, licence free and could be customised to suit input data available in each of the 3 locations. This was of critical importance since the motivation for students was increased by focussing on studying their immediate surroundings. The level of pre-structuring of data which is required for some UBEMS, for example CitySim (Robinson et al., 2009) or Energy Atlas Berlin (Kaden and Kolbe, 2013) which is based on input data in a cityGML format would have restricted the choice of case study context to those for which data had already been prepared. The developed UBEM is based on the modelling requirements of EnergyPlus.

Underlying theory

In London, all students came to the training initiative with a grounding in building physics, in Lima, few students had significant prior experience in building physics. In Ahmedabad, students came from a mix of backgrounds and were assigned to groups to ensure a spread of experience and skills. In all three locations the focus of theory was on how dynamic thermal simulation represented the underlying building physics and how simplification and approximation affected results. Figure 2 illustrates the contents and sequence of teaching for each location.

Results and discussion

Student experience

In each location student feedback on the training initiative was very positive. In Ahmedabad 83% of students rating the initiative as very good or excellent and 13% rating it good. Informal feedback in Lima was positive. In London, student feedback at the midpoint of the module was positive. In all cases students noted that the training initiatives had been demanding, requiring them to develop a range of new skills but that those skills were highly valued.

In all three cases students mastered the technical requirements, producing credible results. The overall standard of work submitted by students for assessment was high. The focus on group reflection resulted in carefully structured scenario evaluation as exemplified by the work by student in Ahmedabad, shown in Figure 3 in which the group evaluated the impact of adjusting the shading in the case study neighbourhood. The value of the work undertaken by the students was demonstrated by the fact that the data collected in Ahmedabad during fieldwork formed ground truth data for subsequent academic work. A number of students on the course have gone on to undertake further academic research in this field, including publishing journal articles which have their origins in the material studied during the training initiative (Mathur et al., 2021). In all locations, student motivation was high - particularly in Lima where students were working on low-income neighbourhoods in parts of the city they would not normally visit. Site visits were facilitated by community representatives who acted as guides and local experts. The community representatives participated in the final review of the students' work, along with academics from all three

Figure 2: Sequence of contents for each course

locations and local NGO partners. In Lima students went beyond the brief for the group work in which each group was asked to work on a separate section of the neighbourhood. For the final review, the 5 groups decided to collaborate and present an analysis for the whole neighbourhood rather than a series of smaller analyses. This resulted in much broader insights and was much more meaningful for the community representatives for which the students were commended.

In London, development of input data models from large public data sets was an important component of the teaching initiative and students were free to select their own neighbourhood for their final assessment. The majority of students selected neighbourhoods with which they had a personal connection. This facilitated critical reflection on the input data and in particular encouraged students to interrogate energy performance certificate data in detail.

Addressing the challenges of UBEM education

In the section entitled Urban building energy modelling we set out our view of the three key challenges for UBEM education:

- The need for a sound understanding of underlying building physics concepts
- Acquisition of the skills required to access, process and critically assess input data
- The ability to critically assess outputs

The results produced by the students demonstrated a strong appreciation of the need for critical appraisal of input data, this was fostered through either site visits (Lima and Ahmedabad) or ongoing critical review and reflection of data for neighbourhoods which

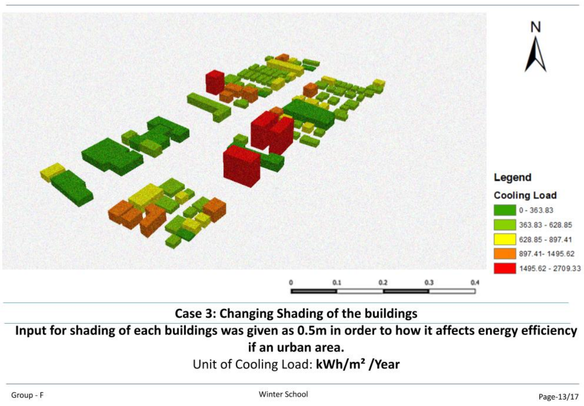

Figure 3: Example of analysis of the impact of varying shading in the study area submitted by students in Ahemdabad

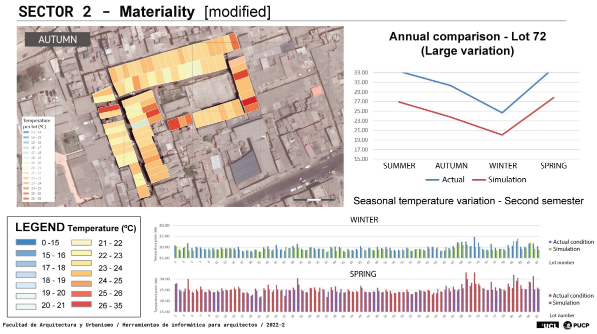

Figure 4: Example of analysis of thermal comfort by floor in the study area submitted by students in Lima

were well known to the students (London). A key challenge for the teaching team in each location was to maintain the focus on the acquisition of data processing skills and critical thinking rather than on mechanical data collection. Teaching initiatives in all three locations were successful in engaging students in a process of critical review and assessment criteria were tailored to support this.

To some extent, the teaching initiatives were able to develop students' understanding of the underlying building physics concepts. This was evident in the structured retrofit scenarios assessed by students in Ahmedabad, for example. Overall, the use of simulation tools appeared to facilitate to an increased understanding of the underlying physical processes which were being modelled in line with Reinhart et al.'s experiences (2015). However, this was not explicitly tested and is an aspect which the authors consider needs to be given greater focus in future training initiatives.

The final challenge, developing critical thinking about outputs is a particularly difficult problem given the complexity of UBEMs. It has repeatedly been observed that it is easier to train students in the procedural steps of simulation for individual building models but much harder to develop the ability to scrutinise outputs (Strachan et al., 2016; Beausoleil-Morrison and Hopfe, 2015, for example). This is com-

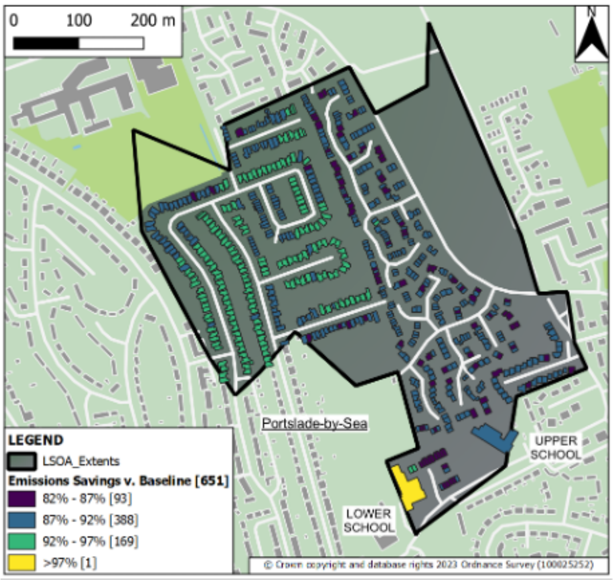

Figure 5: Example of emissions reductions by 2050 due to modelled pathways submitted by students in London

pounded for UBEMs by the complexity and variability of input data and has proved difficult to address in the time available for each initiative. This difficulty was partly driven by a decision to focus on real data and contexts which would be familiar to the students. In the case of London, where aggregate annual meter data was available for each of the study areas and students used this to validate their results. In future training initiatives, attempts will be made to streamline earlier sessions on input data to enable introduction of a set of validation exercise on a prescribed set of test data where empirical data is not available for validation.

Conclusions

Bottom-up building energy modelling requires a sound understanding of the underlying building physics in order to accurately characterise the energy flows into and out of each space. Moving from the individual building to the urban scale brings a need for automatic processing of the large volumes of data needed to characterise the geometry, building fabric, occupancy and loads in a large number of buildings. The skills needed for this exercise are partly dependent on the location which is being modelled and the type of data which is available.

Delivering UBEM education as an adjunct to architecture, urban planning and engineering education is possible but challenging due to time constraints and the diverse range of skills and prior experience of students undertaking an optional module. In this article, we have identified three key challenges for UBEM education and we recommend a continual cycle of critical reflection for educators focused on how successfully these challenges are being addressed. This will be particularly important as the field of UBEM continues to develop and the capability of tools to incorporate additional urban energy flows increases.

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