Towards a universal access to Urban Building Energy Modelling - The case of low-income, self-constructed houses in informal settlements in Lima, Peru

Argyris Oraiopoulos[1], Pamela Fennell[1], Shyam Amrith[1], Martin Wieser[2], Ivan Korolija[1], Paul Ruyssevelt[1]
[1]Energy Institute, University College London, London, UK
[2]Department of Architecture, PUCP University, Lima, Peru

Abstract

By 2050 urban population is estimated to grow from 4 billion to almost 7 billion, with over 90% expected in the Global South, where development often takes place as unplanned informal settlements, with essential shortage of critical infrastructure. In processing some of the associated rising challenges, Urban Building Energy Models can play a key role. However, such models have had limited presence in this context, highlighting the inequalities in the representation of such communities in this field. This paper works towards addressing this gap and presents the development of an Urban Building Energy Modelling workflow for analysing the thermal comfort in a self-constructed, low-income housing neighbourhood in Lima, Peru, using an innovative approach, based largely on open source software, such as EnergyPlus, QGIS and Python. The results highlight that the compact and dense built form of the building blocks, can cause higher heat retention, especially in lower thermal zones and therefore result in high indoor temperatures for longer. Additionally, the poor thermal performance of the buildings' fabric, can cause hourly indoor temperatures to rise to critical levels, especially in higher thermal zones, which can have adverse impacts on the residents' health. This first step in understanding some of the key issues these communities are facing, is critical in the early assessment of future building retrofit decisions.

Introduction

Urban areas are currently home to 55 per cent of the world's population, using two-thirds of the world's energy use, while generating 70 per cent of global carbon emissions UNEP (2020). Buildings play a centre role to this, collectively being responsible for over a third of global energy use and related greenhouse gas (GHG) emissions. To that end, modelling tools, which allow the analysis and prediction of energy demand in buildings on a large scale, have increasingly been of interest to researchers, practitioners and policy makers. As such, Urban Building Energy Models (UBEMs) have, over the past few years, been established as a useful tool for processing some of the challenges the built environment is facing Johari et al. (2020)) . However, the development of UBEMs has been based on research conducted mainly in the Global North, where progress in data availability has been significant over the last decade.

A recent review of the literature suggested that coverage of UBEM research is much greater in the USA and Europe than the rest of the world, with low- and middle-income countries in South America, Africa and Southern and South-East Asia, being notably absent Fennell et al. (2019). This inequality regarding the representation of communities of the Global South in UBEMs has only recently started being addressed Janda et al. (2019), with researchers focusing on Sustainable Development Goal (SDG) 11 of the United Nations 2030 agenda, which aims to "make cities and human settlements inclusive, safe, resilient and sustainable" UN (2015). This focus can also be linked to other SDGs including SDG1 on ending poverty, SDG3 on ensuring healthy living, SDG7 on access to energy, SDG10 on reducing inequality, SGD13 on combating climate change and SDG16 on inclusive societies, enhancing the importance of such work.

By 2050 urban population is estimated to rapidly grow from 4 billion to almost 7 billion, with over 90% expected to take place in the Global South and especially in low- and middle-income countries in East and South Asia, Africa and Latin America UN-HABITAT (2018). Rapid urbanisation in such regions is often insufficiently planned and in practice linked with self-constructed neighbourhoods, often referred to as unplanned informal settlements, with essential shortage of critical infrastructure and basic services, leaving residents in urban poverty and highly vulnerable to climate change UNDP (2017); The Lancet (2017). Faced with the prospect of this challenging urbanisation, it is essential for policymakers in the Global South to have access to tools that can adequately capture the needs of these marginalised communities, in order for them to be part of a fully inclusive planning and continue to grow without experiencing such increasing inequities.

This paper presents one of the first attempts to develop a modelling framework for analysing and predicting the energy demand and thermal comfort of an informal settlement in the Global South. The UBEM presented here addresses the issue of inclusiveness by modelling a low-income, self-constructed housing neighbourhood in Lima, Peru, using an innovative approach based largely on open source software. Drawing from the knowledge and experiences of academics, practitioners, policy makers and residents, it aims to create an inclusive framework that can address the current and future challenges in the rapidly developing and expanding cities of the Global South.

Background

Urban Building Energy Models (UBEMs) have been developed and utilised for many years Elmar Reiter (1980); Rickaby (1991); Adolphe (2001), but their plethora has significantly been increased over the last decade Swan and Ugursal (2009); Reinhart and Cerezo Davila (2016); Malhotra et al. (2022). Making use of existing open source software like EnergyPlus Sokol et al. (2017) or creating customised modelling suites Fonseca and Schlueter (2015); Schiefelbein et al. (2019), researchers have been able to analyse the energy demand of urban areas spanning from a small number of buildings Nageler et al. (2018) to millions Krarti et al. (2020), transforming UBEMs to a powerful tool which can be used in numerous applications Ang et al. (2020).

One of the benefits in recent years has been the increased availability and accessibility to large datasets, which can be configured accordingly to fit the needs of individual models, using open source platforms and software Malhotra et al. (2022); Schiefelbein et al. (2019). However, even in data-rich urban settings, the level of detail in large scale datasets is often limited. This results in simplified methods, that although in some cases can enhance the practicality of the models Johari et al. (2022); Zekar and Khatib (2018), in most cases produce an output with large uncertainties in relation to its intended application Oraiopoulos and Howard (2022). Although some variability in the results is to be expected, due to the inherent large variation in the buildings' composition as well as operations, there exist approaches to reduce the resulted uncertainty in the output Calama-González et al. (2021); Sokol et al. (2017); Risch et al. (2021); Fennell et al. (2021); Prataviera et al. (2022).

While there are considerable challenges during the development of UBEMs in data-rich urban settings, these challenges are even more prevalent when it comes to developing UBEMs for low-income, self-constructed neighbourhoods in the Global South. These communities are often underrepresented partly due to policies that fail to adequately address issues of social equity, hence omitting large parts of the population from future climate resilience and adaptation programs Meerow et al. (2019); Anguelovski et al. (2016). It is therefore evident, that these data-scarce areas need innovative and rather tailored methods, in capturing adequate information, in order to develop suitable UBEMs for addressing the energy challenges of these rapidly expanding regions Mathur et al. (2021).

The remaining of this paper will present the methodology of the developed UBEM for a low-income, self-constructed housing neighbourhood in Lima, Peru, as well as the results from the building energy simulations, together with a discussion on the potential impact and future steps of this work.

Methodology

This study follows the recommendations of previous research Nägeli et al. (2022); Oraiopoulos and Howard (2022) in developing and presenting UBEMs for the building performance simulations of a low-income housing community. Initially the aim of the model will be defined by explaining the application of this UBEM. The computational method of the model will then be described and its components will be outlined. Following, the input data, critical parameters and key assumptions made will be presented, and the quality assurance in the form of calibration and validation of the model will be explained.

Study area

The area of focus in this work is the district of El Agustino in Lima, Peru's capital city and the second driest metropolis in the world. Lima has more than doubled its population since 1980 to almost 10 million, with this rapid growth taking form both in terms of outward expansion and inward densification. Currently, an estimated 30% of the population occupies land on the steep peripheral slopes, beyond the metropolitan boundaries, in self-constructed neighbourhoods. Residents in these peripheral areas often lack basic services like water and electricity for many years, while they wait to be connected to the main utilities system. On the other hand, within the overcrowded areas of the inner city, people often live in precarious conditions, around dysfunctional infrastructure, in deteriorating buildings, exposed to everyday risks which include fires from unsafe power connections Lambert and Allen (2017). The UBEM will include 165 buildings located in three blocks in the El Agustino area. These are presented in the following section where the building geometry input to the model is explained.

Most residential buildings comprise of a single floor space, with some buildings extending up to 6-7 floors while also housing a commercial space on the ground floor. The essential need for building renovation and redevelopment in these areas could result in a displacement of the occupants towards the peripheral areas, mainly due to their exclusion from the decision making processes. This would have and adverse

Figure 1: Lima, El Agustino boundaries in red (Google Maps)

impact on their social networks and cost of living due to the increased distance to employment opportunities and services.

Aim/Application

The aim of this work is to address the invisibility of informal settlements in UBEMs. In particular, this paper examines the representation of thermal comfort practices of low-income housing occupants in informal settlements. From the methods for data collection, to the development of a computational approach and the analysis of results, the output of this work aims to act as catalyst information for the equitable urban development of marginalised communities. The grounded data and local expert knowledge, play a key role for the diverse range of housing and occupant practices to be explored and simulated, using state of the art software and modelling approaches.

Computational Method

The computational method for the UBEM is based on the freely available, dynamic thermal simulation software EnergyPlus, which runs through a customised Python script. The SimStock model workflow Korolija (2020), presented in Figure 2, comprises of consecutive steps. Initially, the input data are collected and arranged in a GIS platform, 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. For this work, SimStock was operated through a dedicated plugin interface that has been developed in QGIS, a free and open-source cross-platform desktop geographic information system application (REF).

Input Data & Key Assumptions

The developed UBEM is based on the modelling requirements of EnergyPlus and as such the main input data categories are:

- Building geometry
- Building fabric
- HVAC systems and controls

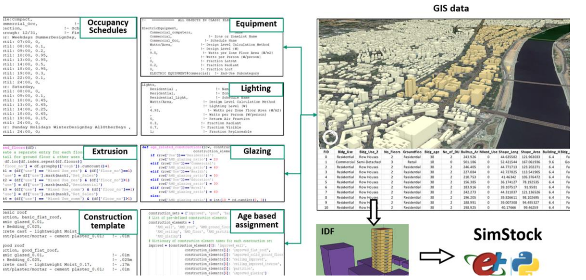

Figure 2: SimStock workflow (adopted from Mathur et al. 2021)

- Internal gains (equipment, lights, people)
- Occupancy schedules
- External Weather

These can be characterised as measured, estimated, assumed or missing, according to whether these where collected, processed or selected based on scientific knowledge and theory, or if they are required but are completely absent from the calculations.

The building geometry of the 165 buildings in the three blocks in El Agustino was estimated using data from a drone survey. The area of focus, was surveyed using a drone, flying at a height range of between 50-100 metres. The data were collected using photogrammetry, utilising the drone's three cameras, taking photos from three different angles at a 4K resolution. In El Agustino, the drone completed 10 flights, capturing a large area, presented in Figure3 (left) by the yellow and red pins. The presented work focuses on the data collected from a single flight, shown with red pins in Figure3 (left) and within the red line borders in Figure3 (right).

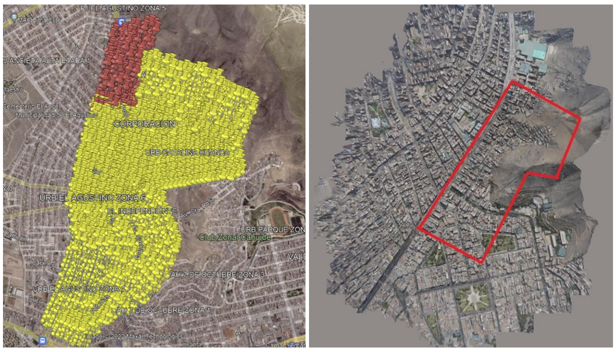

Figure 3: All drone flights in El Agustino in yellow pins, with the study area in red pins (left), the study area, depicted within the red line borders (right)

Following the photogrammetry process, the Context Capture software by Bentley Systems, was employed to create the 3D reality mesh of the area in this single drone flight, presented in Figure4.

This allowed for a substantially clearer identification of the buildings' footprints, as it can be seen in Figure5, where the compiled drone images are visually compared to the same area as captured by the Google

Figure 4: View angle of the 3D reality model of the study area in El Agustino, product of the Context Capture software

Earth satellite image.

The footprints of the buddings were manually hand-drawn as polygons in QGIS at this stage (Figure6), using the ground plan of the photogrammetry result, as well as the 3D reality model. The building's footprints were inferred based on the visual inspection of the differences in the elevation of the buildings as well as the roof constructions and backyard openings.

Making further use of the data captured from the drone, a Digital Elevation Model (DEM) was produced in QGIS, allowing for the heights of buildings to be calculated. It has to be noted that the Mean Sea Level (MSL) that was applied in order to increase the accuracy of the approximation of the buildings' heights in El Agustino was taken as 211m. Utilising the estimated buildings' heights, an assumption of 3 metres per floor was used in order to create the buildings' floors, which represent the thermal zones is SimStock. The final geopackage files for input in the newly developed QGIS plugin, were created using the buildings' footprints, heights and number of floors. Figure7 shows the extruded polygons in the study area, using the QGIS Qgis2threejs plugin, and the 3d reality model of the same building blocks.

The fabric of the buildings was largely estimated based on the visual inspection of the buildings in the 3D reality model, as well as the sharing of local knowledge from experts in the Pontifical Catholic University of Peru (PUCP), in Lima. Initially a 40% window-to-wall ratio was assumed, with single glazed window openings. At its current form, the newly developed QGIS plugin for SimStock, only allows for the main fabric elements of external walls, roofs and ground floor to be specified. The construction of external walls was assumed as uniform across all buildings in the study area, and was set as uninsulated brick with cement layers internally and externally, giving an overall U-value of 2.184 W/m^2°C. There were two types of roof assigned to the buildings, a steel corrugated sheet or a lightened reinforced concrete ceiling, with U-values of 3.704 W/m^2°C and 3.130 W/m^2°C respectively, and one type of ground floor, a solid concrete floor slab. For the rest of the fabric elements, such as floors, ceilings and partition walls, Energyplus default settings were used.

Figure 5: Visual comparison between the drone image of some buildings in the study area (top) and the satellite equivalent from Google Earth (bottom)

The HVAC systems and controls in these low-income houses in El Agustino, are very rarely present, with residents often experiencing the adverse effects of free-floating internal spaces all year round. Therefore, for the purposes of this work, the heating and cooling loads during the UBEM simulations were completely switched off.

In terms of internal gains, the assumptions for all houses were 25 Watts per zone floor area for electrical equipment, 12 Watts per zone floor area for lighting and 2 people per m$^2 of floorarea$.

Figure 6: Footprint extraction of the study area in El Agustino, Lima

Figure 7: The extruded polygons in the study area and the 3D reality model of the same area in El Agustino, Lima

The occupancy schedule was applied uniformly for all building thermal zones and it is outlined in Table 1 below:

The climate in Lima is characterised as mild, despite its location in the tropics and in a desert. The temperature typically varies from 15°C to 27°C and is rarely below 12°C or above 30°C wea (2022)). The weather file (.epw) that was used for the UBEM simulations was acquired from the Climate.OneBuilding.Org project cli (2022).

Table 1: Occupancy schedule for weekdays and weekends

Hours	**Weekdays**	**Weekends**
07:00-09:00	1	1
09:00-17:00	0.5	1
17:00-19:00	0	1
19:00-24:00	0.5	0.5
24:00-07:00	1	1

Quality Assurance

The purpose of this paper is to present a methodology for the modelling of communities that have commonly been excluded from the field of UBEM. In this attempt the primary objective is to produce a workflow that results in the dynamic thermal simulation of a large number of buildings. Therefore, the quality assurance of the output, although of significant importance, here it falls outside the scope of the paper. The authors recognise that the processes of calibration and validation should be an integral part of any modelling approach, however, mainly due to the lack of available data at the time of submission, this paper is unsuccessful in supporting such practises. Here it has to be noted that local surveys, in partnership with the local community, capturing parameters such as occupancy, heating and cooling practises, uses of lights, appliances, and measured internal temperatures, are currently underway in houses in Lima and future work will incorporate these into the workflow, especially in the calibration process.

Results & Discussion

The modelling for the three building blocks in El Agustino produced 165 building simulations in EnergyPlus. Though only 156 buildings were successfully completed, with further investigation on the reason 9 buildings did not manage to produce results pending. The software was operated on a Windows 10 laptop with an i7 Intel Core processor at 3.00GHz and 16GB RAM. The simulation time was about 8 minutes and the QGIS plugin produced two CSV files, one containing a series of reports regarding all input and output parameters and one with the time series data of operative temperatures in all thermal zones (one per floor). This data was used to explore the indoor thermal environment in these self-constructed low-income housing buildings. The recommendations by the World Health Organisation (WHO) outline that ”an indoor temperature between 18-24°C offers little thermal threat to appropriately clothed sedentary people (when air movement is of less than 0.2m/s, a relative humidity of 50% and a mean radiant temperature within 2°C of air temperature)” WHO (1987). Therefore, an initial analysis explored the amount of hours in a year during which the indoor temperature in a thermal zone (a floor of a building) was above 24°C (future work will see the application of the adaptive thermal comfort approach, with wider temperature envelopes). This was applied for all 156 successfully simulated buildings. The results are summarised in Table 2.

The scale of the analysis requires an aggregation to be applied in this first instance. The results in Table 2 indicate the percentage of buildings where the indoor temperature of a thermal zone is above 24°C for a percentage range of hours in a year (i.e. 100% being all year round, 8760 hours). Therefore, for example looking at the table, in 84% of the buildings the first floor thermal zone has an indoor temperature above 24°C between 90-100% of all hours in a year. The results revealed that all thermal zones in all buildings have an indoor temperature above 24°C, for at least 60% of all hours in a year. Furthermore, the findings show that the lower the floor is, more hours on internal temperature above 24°C and hence the higher the indoor temperatures remain throughout the year. This possibly indicates that the compact and dense built form of the blocks, especially in the case of the lower floors, results in higher heat retention perhaps due to lower infiltration and ventilation rates, since there are fewer exposed walls in these zones. From this result it can be concluded that probably occupants in lower floors experience thermal discomfort for longer periods of time in a year. This though could only be confirmed by conducting a thermal comfort survey in these houses. Perhaps occupants are accustomed to the higher indoor temperatures and find thermal discomfort not an issue of significance in their everyday lives. It has to be noted that the same method was applied to explore the amount of hours when the indoor temperature in thermal zones was below 18°C. The results showed that this can be a rather insignificant issue as at most there was a 2% of annual hours below 18°C for a single thermal zone.

Having initially explored the overall indoor thermal environment in the buildings, the next step was to investigate the extreme indoor temperatures in the thermal zones. This was done by inspecting the maximum and minimum indoor hourly temperatures in a year. The results are presented in Figure 8 and Figure 9.

Figure 8 shows the frequency distribution of annual maximum indoor temperatures by thermal zone in all 156 simulated buildings in El Agustino. Overall, it can be observed that the higher the floor, the higher the hourly maximum indoor temperatures can get in the year. This is to be expected as the higher the floors the more exposed are to solar radiation and to buoyancy driven heat gains from lower thermal zones. The graph further shows that extreme indoor temperatures (above 35°C) are not rare even in the lower floors of buildings, in Lima's climate. This can be partly attributed to the very poor thermal performance of the buildings' fabric, but also an overestimation of ventilation and underestimation of infiltration rates in the model.

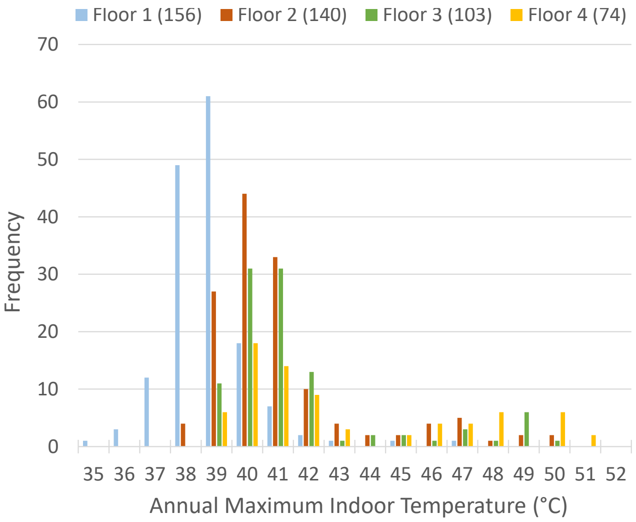

Figure 8: Frequency distribution of annual maximum indoor temperature by thermal zone, in the study area

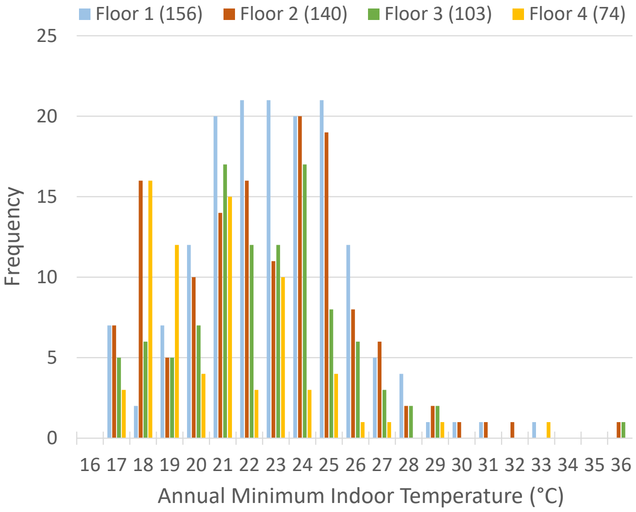

Figure 9: Frequency distribution of annual minimum indoor temperature by floor, in the study area

Figure 9 shows the frequency distribution of annual minimum indoor temperatures by thermal zone. Overall, it can be observed that the minimum indoor temperatures throughout the year can present a much wider range compared to the maxima. Here the results show that the higher the floor of a building, the lower the hourly minimum indoor temperature in the year. Indicating that heat loses are larger in higher floors, which is to be expected given the fact that the thermal mass of some the modelled roofs is very low, since there is no insulation, resulting in increased heat losses through the fabric.

Limitations and Future work

Overall, the results can be explained by the nature of the built form and the fabric of the simulated buildings. However, this work has had a number

Table 2: Percentage of buildings where indoor temperature in a given thermal zone is above 24° C for a given range of hours in a year, the numbers in parenthesis indicate the sample size (i.e., 156 the number of first floors in the study area)

% of hours in a year	**Floor 1 (156)**	**Floor 2 (140)**	**Floor 3 (103)**	**Floor 4 (74)**	**Floor 5 (27)**	**Floor 6 (12)**	**Floor 7 (4)**
61-70	5.1	3.6	2.9	1.4	18.5	8.3	0.0
71-80	3.2	11.4	7.8	25.7	18.5	8.3	25
81-90	7.7	5.7	8.7	18.9	3.7	25.0	50
91-100	84.0	79.3	80.6	54.1	59.3	58.3	25

of limitations that can significantly impact the results. First and foremost, the buildings footprints have been extracted using manually drawn polygons. For this workflow to be applied to a much greater area, comprising thousands of buildings, this process would have to be automated. This is the immediate next step in the future work. Secondly, the thermal zones of the buildings have been based on the estimated footprints from the drone surveys, as the external images of the houses reveal very little regarding the internal layout of these buildings. Thirdly, the applied variables for the fabric have only been assumed based again on the visual inspection of the drone images and grounded expert knowledge, with no data in hand. The same window to walls ratio has been applied to all buildings' external walls, when it is clear from viewing the 3D reality model that many of the external walls do not have any openings. In addition the assumptions for internal heat gains as well as occupancy schedules, and use-types, and their assignment to all buildings, eliminates and diversity in the uses of buildings. Many of these limitations can be partly overcome by extracting information from the local census surveys, and applying a set of distributions based on such datasets, instead of fixed values. Lastly, the calibration and validation of the presented UBEM is essential for any of the results to act as evidence in evaluating future retrofit decisions. Both quantitative and qualitative data, such as indoor temperatures and grounded heating practises, have been collected during the duration of this project and will be used to calibrate the modes and ensure the quality of future outputs. Finally, future work will test free and open software across the whole workflow, to eliminate any dependency on expensive licences. This will allow the full democratisation of the proposed UBEM, empowering communities to act and improve their living environments.

Conclusion

This paper presented a modelling workflow for analysing the thermal comfort in a low-income housing neighbourhood in Lima, Peru. The Urban Building Energy Model was developed using an innovative approach based largely on open source software. Drawing from the grounded knowledge and experiences of local academics, practitioners and policy makers, it initiated the development of an inclusive framework that can address the issue of inclusiveness of the rapidly developing cities of the Global South, in Urban Building Energy Modelling.

A newly developed QGIS plugin was used as the interface for the SimStock model, which batch simulates buildings in EnergyPlus via a Python script. A drone survey was administered in El Agustino, Lima, allowing for increased precision in estimating the geometry and fabric of buildings. Other input assumptions, such as HVAC systems and occupancy, were based on explicit knowledge from local experts. The results indicate that the compact and dense built form of the blocks, especially in the lower floors of buildings, can cause higher heat retention, and therefore result in high indoor temperatures for longer. On the other hand, the lack of energy efficiency measures, especially in external walls and roofs, can cause hourly indoor temperatures to rise to perilous levels that can have adverse impacts on residents' health.

The prospective calibration and validation of the model using measured data, will allow the careful evaluation of retrofit strategies, which are critical for improving the living conditions of low-income residents, in informal settlements across the Global South.

Acknowledgement

This work was funded through a UKRI collective fund as part of the GEMdev project, GEMDdev: Grounded Energy Modelling for equitable urban planning development in the global South [ES/T007605/1].

References

(2022, 9). Climate.OneBuilding.Org.

(2022, 9). weatherspark.com.

Adolphe, L. (2001). A simplified model of urban morphology: Application to an analysis of the environmental performance of cities. Environment and Planning B: Planning and Design 28(2), 183–200.

Ang, Y. Q., Z. M. Berzolla, and C. F. Reinhart (2020, 12). From concept to application: A review of use cases in urban building energy modeling. Applied Energy 279.

Anguelovski, I., L. Shi, E. Chu, D. Gallagher, K. Goh, Z. Lamb, K. Reeve, and H. Teicher (2016, 9). Equity Impacts of Urban Land Use Planning for Climate Adaptation: Critical Perspectives from the Global North and South. Journal of Planning Education and Research 36(3), 333–348.

Calama-González, C. M., P. Symonds, G. Petrou, R. Suárez, and L. León-Rodríguez (2021, 1). Bayesian calibration of building energy models for uncertainty analysis through test cells monitoring. Applied Energy 282.

Elmar Reiter (1980). Energy Consumption Modelling. Technical report, National Oceanic and Atmospheric Administration.

Fennell, P. J., I. Korolija, and P. Ruyssevelt (2021). A comparison of performance of three variance-based sensitivity analysis methods on an urban-scale building energy model. In Proceedings of the 17th International Building Performance Simulation Association Conference 2021.

Fennell, P. J., P. A. Ruyssevelt, R. Rawal, and V. Poola (2019). Determining the most appropriate form of Urban Building Energy Simulation Model for the city of Ahmedabad. In Proceedings of the 16th International Building Performance Simulation Association Conference 2019.

Fonseca, J. A. and A. Schlueter (2015, 3). Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts. Applied Energy 142, 247–265.

Janda, K. B., P. Fennell, C. Johnson, J. Tomei, and X. Lemaire (2019). Towards inclusive urban building energy models: incorporating slum-dwellers and informal settlements (IN-UBEMs). In European Council for an Energy Efficient Economy Smmer Study 2019.

Johari, F., J. Munkhammar, F. Shadram, and J. Widén (2022, 3). Evaluation of simplified building energy models for urban-scale energy analysis of buildings. Building and Environment 211.

Johari, F., G. Peronato, P. Sadeghian, X. Zhao, and J. Widén (2020, 8). Urban building energy modeling: State of the art and future prospects. Renewable and Sustainable Energy Reviews 128.

Korolija, I. (2020). SimStock-A modelling platform generating dynamic building energy simulation models. Technical report, UCL Energy Institute, London.

Krarti, M., M. Aldubyan, and E. Williams (2020, 3). Residential building stock model for evaluating energy retrofit programs in Saudi Arabia. Energy 195.

Lambert, R. and E. Allen, A (2017). Participatory mapping to disrupt unjust urban trajectories in Lima. In P. Imperatore (Ed.), Geospatial Technology. Rijeka, Croatia: InTech Open Access.

Malhotra, A., J. Bischof, A. Nichersu, K. H. Häfele, J. Exenberger, D. Sood, J. Allan, J. Frisch, C. van Treeck, J. O'Donnell, and G. Schweiger (2022, 1). Information modelling for urban building energy simulation—A taxonomic review. Building and Environment 208.

Malhotra, A., M. Shamovich, J. Frisch, and C. van Treeck (2022, 1). Urban energy simulations using open CityGML models: A comparative analysis. Energy and Buildings 255.

Mathur, A., P. Fennell, R. Rawal, and I. Korolija (2021). Assessing a fit-for-purpose urban building energy modelling framework with reference to Ahmedabad. Science and Technology for the Built Environment 27(8), 1075–1103.

Meerow, S., P. Pajouhesh, and T. R. Miller (2019). Social equity in urban resilience planning. Local Environment 24(9), 793–808.

Nageler, P., A. Koch, F. Mauthner, I. Leusbrock, T. Mach, C. Hochenauer, and R. Heimrath (2018, 11). Comparison of dynamic urban building energy models (UBEM): Sigmoid energy signature and physical modelling approach. Energy and Buildings 179, 333–343.

Nägeli, C., C. Camarasa, M. Delghust, P. Fennell, I. Hamilton, M. Jakob, J. Langevin, J. Laverge, J. L. Reyna, N. H. Sandberg, and J. Webster (2022, 4). Best practice reporting guideline for building stock energy models. Energy and Buildings 260.

Oraiopoulos, A. and B. Howard (2022, 4). On the accuracy of Urban Building Energy Modelling. Renewable and Sustainable Energy Reviews 158.

Prataviera, E., J. Vivian, G. Lombardo, and A. Zarrella (2022, 4). Evaluation of the impact of input uncertainty on urban building energy simulations using uncertainty and sensitivity analysis. Applied Energy 311.

Reinhart, C. F. and C. Cerezo Davila (2016, 2). Urban building energy modeling - A review of a nascent field. Building and Environment 97, 196–202.

Rickaby, P. A. (1991). Energy and urban development in an archetypal English town. Environment and Planning B: Planning and Design 18(8), 153–175.

Risch, S., P. Remmen, and D. Müller (2021, 1). Influence of data acquisition on the Bayesian calibration of urban building energy models. Energy and Buildings 230.

Schiefelbein, J., J. Rudnick, A. Scholl, P. Remmen, M. Fuchs, and D. Müller (2019, 2). Automated urban energy system modeling and thermal building simulation based on OpenStreetMap data sets. Building and Environment 149, 630–639.

Sokol, J., C. Cerezo Davila, and C. F. Reinhart (2017, 1). Validation of a Bayesian-based method for defining residential archetypes in urban building energy models. Energy and Buildings 134, 11–24.

Swan, L. G. and V. I. Ugursal (2009, 10). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews 13(8), 1819–1835.

The Lancet (2017, 4). Urbanisation, inequality, and health in Asia and the Pacific. The Lancet 389(10077), 1370.

UN (2015). Transforming our world: the 2030 Agenda for Sustainable Development. Technical report.

UN-HABITAT (2018). Addressing the most Vulnerable First - Pro-Poor Climate Action in Informal Settlements. Technical report.

UNDP (2017). Leveraging Urbanization and Governance for Growth in Africa: A Framework for Action. Technical report.

UNEP (2020). 2020 Global Status Report for Buildings and Construction, Towards a zero-emissions, efficient and resilient buildings and construction sector. Technical report, Global Alliance for Buildings and Construction.

WHO (1987). Health impact of low indoor temperatures.

Zekar, A. and S. E. Khatib (2018, 8). Development and assessment of simplified building representations under the context of an urban energy model: Application to arid climate environment. Energy and Buildings 173, 461–469.