INTERNATIONAL
BUILDING
PERFORMANCE
SIMULATION
ASSOCIATION
ENGLAND

Proceedings of BSO-VI 2022
Sixth Building Simulation and Optimisation Virtual Conference
13 - 14 December 2022
Hosted by University of Bath, UK

Developing an Open Access Plugin for Urban Building Energy Modelling in QGIS

Shyam Amrith[1], Argyrios Oraiopoulos[1], Ivan Korolija[2], Pamela Jane Fennell[1]
[1]Energy Institute, University College London, London, UK
[2]Institute for Environmental Design and Engineering, University College London, London, UK

December 2, 2022

Abstract

Urban Building Energy Modelling has gained increased recognition over the past years, with many research teams developing custom modelling suites that can be used for numerous applications. However, in many cases the licensing costs, lack of transparency, the reduced capabilities of selected computational methods as well as the necessity for advanced computing skills, have restricted the wider uptake and utilisation of various developed programmes, especially in regions of the Global South and more specifically in low- and middle-income countries in South America and Southern Asia.

This work presents the first stages in the development of a freely available, open-source tool, able to perform dynamic thermal simulations of a large number of buildings, using a state of the art modelling engine within a user-friendly interface. The novel SimStock plugin for QGIS is able to run multiple EnergyPlus simulations through a customised Python script, for large numbers of buildings, by supporting the viewing, editing and analysis of input and output data in a geospatial format. A key feature of the tool is its ability to work with differing levels of detail in the required input data and therefore overcome a significant barrier to access for UBEMs in the Global South.

This paper outlines the approach and the key components of the tool and further presents its application on two case studies, a densely populated building block in Lima, Peru, and a residential area in the city of Ahmedabad in India. By bringing the latest developments in UBEM to the context of the Global South, this work contributes to the continuous efforts for improving the aspects of inclusiveness, transparency and reproducibility in this field.

Introduction

The scale and urgency of the challenges in decarbonising global building stocks are well documented (Ritchie et al., 2020). For policy makers, local authorities, building owners, understanding the impact of measures and policies across large stocks of buildings is critical to driving the pace of change required. Consequently, the interest in Urban Building Energy Modelling has increased as highlighted by a recent review by Ali et al. 2021.

Urban Building Energy Models (UBEMs) are large-scale models which incorporate representations of large numbers of individual buildings in order to create a model of a neighbourhood or even an entire city (Swan and Ugursal, 2009). Physics-based UBEMs are used to calculate the energy demand of individual buildings or premises based on calculating heat and energy flows, both within the buildings and to and from their surroundings (Ferrando et al., 2020). These models vary considerably in their complexity and the spatial and temporal resolutions in which they are evaluated; however, all require:

- a representation of the geometric and thermophysical properties of the building stock, for example, the area of walls and their ability to transmit heat;
- the energy practices of occupants and the ways in which they interact with the built environment, including the use of energy consuming appliances;
- details of the energy conversion systems and their controls, within the buildings, such as heating, cooling or lighting systems.

UBEMs, in general, require large quantities of data to characterise a whole building stock (Reinhart and Davila, 2016). Therefore, models often develop proxies, averages, and simplified computational methods and assumptions to manage this process. This can greatly impact the accuracy of the output (Oraiopoulos and Howard, 2022). Nonetheless, UBEMs can make important contributions to a number of applications, such as: diagnosing energy demand across a building stock and allowing energy efficiency interventions to be targeted at areas of greatest need (Jahani et al., 2020), assessing the impact of potential intervention strategies across the stock (Krarti et al., 2020; Deru et al., 2011); predicting energy demand and assessing extreme scenarios (Katal et al., 2019);

exploring the impact of renewable energy strategies (Ang et al., 2022)

Although there has been a substantial increase in the interest towards UBEMs the past years, Fennell et. al.'s 2019 review of the literature suggests that model developments have been mainly concentrated on the USA and Europe, with China also reasonably well represented. However, most importantly, coverage is notably absent in low- and middle-income developing countries, in South America, Africa and Southern and South-Eastern Asia. In order to enable more wide-spread use of UBEMs, particularly in the Global South, it is necessary to address a number of barriers:

- licensing costs can present a significant barrier to uptake, particularly in early, exploratory phases of work;
- implementations for a single operating system restrict access for those using other operating systems;
- input data formats can create a large volume of work when existing data needs to be compiled into specific formats in order to be used;
- simplified computational methods can restrict context specific modelling;
- advanced computing skills and more specifically the need to write code, in order to run a model or format input data, can restrict access to those who have the necessary skills.

A number of top-performing tools have successfully addressed these issues independently, but no single one has been able to attend to all of them. For example, the City Building Energy Saver (CityBES) developed at LBNL is aimed primarily for the U.S. building stock, and it is also a web-based tool which can practically be used across operating systems, however access to an internet connection is essential (Chen et al., 2017). Urban Modeling Interface (UMI) developed at MIT can only operate in a Windows environment and requires a Rhinoceros licence (Davila et al., 2016). SimStadt, developed by the University of Stuttgart, is not publicly available (Nouvel et al., 2015), same as the Urban Renewable Building and Neighbourhood Optimization (UrbanOpt) tool developed at the U.S National Renewable Energy Laboratory (NREL) (Polly et al., 2016). CitySim Pro, developed by EPFL researchers, although freely available can only be installed in computers running Windows, and due to the simplified reduced order resistor-capacitor (RC) computational method, it simulates each building as a single thermal zone, offering reduced modelling capabilities (Coccolo et al., 2018). This barrier of the RC computational method is also found in the City Energy Analyst (CEA), developed at ETH Zurich, despite its recent improved ability to run on a macOS operating system (Fonseca et al., 2016).

SimStock, developed at UCL (Claude et al., 2019; Korolija, 2020), is freely available and open source, and it can run across all main operating systems. Moreover, it can perform dynamic thermal simulations of buildings using one of the most established and advanced whole-building energy modelling tools, EnergyPlus (Crawley et al., 2001). However, it requires advanced computing skills and specifically good knowledge of the programming language Python. Consequently, there was a need to develop a new user-friendly interface for SimStock, which would be fully accessible, freely available and open-source, enabling the wide-spread use of the tool. A further aim has been to develop an interface which would enable models to be generated from widely varying datasets to avoid restricting the tool to a single context. The development of an interface for SimStock has been the main subject of this work and all aspects of this process are documented in this paper.

The remaining sections present the methodological approach in developing the plugin, in terms of required inputs, computational method and final outputs, as well as some case study examples where the plugin has been tested, and the corresponding results together with the planned future work.

Method

The research team have previously developed the SimStock modelling platform (Claude et al., 2019), which automatically generates dynamic thermal simulation models of all buildings within an area of analysis ready to be executed by EnergyPlus, given a set of input data. SimStock is Python-based and while it has been used for a wide range of scenario analyses in a number of different contexts (Claude et al., 2019; Mathur et al., 2021; Fennell et al., 2021; Schwartz et al., 2021), this has always been with close support from the research team, as the tool has no user interface, and exists in the form of a series of Python scripts. Since a significant proportion of the SimStock code is related to geometric processing, a decision was taken to develop the tool as a plugin for QGIS. The schematic in Figure 1 outlines the basic workflow of the plugin.

QGIS is an open-source Geographic Information System which runs on most Unix platforms, Windows, and macOS. It further offers significant capabilities as a user interface platform for SimStock, since it allows the creation and import of geometry, management of data, simulation and analysis and visualisation of results, all to be carried out within a single interface.

Inputs

The starting point with regards to the input data is a QGIS 2D vector layer containing the geometrical features of the buildings (i.e. buildings' footprints). There are no requirements regarding the source of this data; for example the geometry could be obtained from digitised maps, hand-drawn or generated via any other suitable method. The polygons are then transferred to SimStock directly from the feature ge-

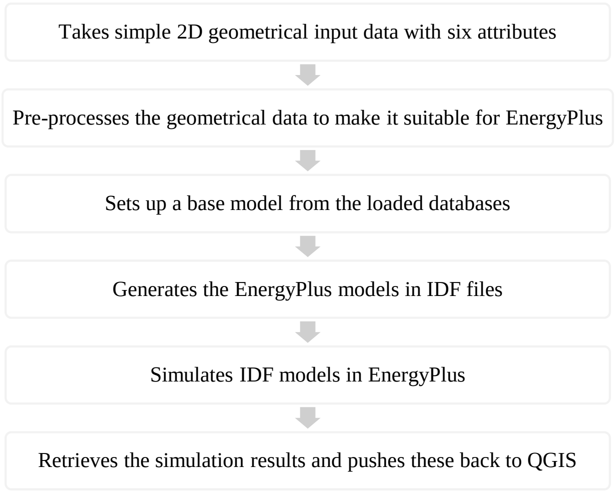


Figure 1: Basics steps of the workflow for the SimStock plugin for QGIS

ometries themselves using the built-in QGIS Python API. Once this vector layer is formed in QGIS, the launch of the SimStock plugin adds a series of unique attribute fields to its attribute table, where all other polygon-level input data are specified. Following are the basic attributes (and their data type in parentheses) as currently formed at the time of writing this paper:

- *Unique identifier (string)*

  Automatically generated. This is used by SimStock to name and identify zones and objects in the EnergyPlus model which belong to the given polygon. It is also used to retrieve the simulation results.

- *Building height (float)*

  The height of the polygons expressed in metres (m).

- *Shading (boolean)*

  False – Building is included in the energy modelling.

  True – Building is treated as a shading block.

- *Window-to-wall/glazing ratio (float)*

  The ratio between the surface area of the window opening and the surface area of the wall for a given building, expressed as a percentage.

- *Number of floors (integer)*

  Number of floors in the building. Determines how many thermal zones are stacked vertically within the EnergyPlus model for the given polygon.

- *Construction (string)*

  Used to select a construction preset from the database.

- *Overhang depth (float)*

  Optional input. Whether a shading overhang should be added to the windows and if so, to what depth (in metres).

- *Floor use (string)*

  Specifies the use of the given floor (e.g. residential, commercial) so that appropriate database objects can be assigned to the zone.

The above attributes summarise the minimum input data required to run SimStock using this plugin. The plugin allows for specifying much more detailed inputs via a comprehensive database, which handles the bulk of the information used to create the EnergyPlus models. If this step is omitted then the plugin will simply use a series of default settings, which is viewable in session.

This database hosts a set of default Intermediate Data Format (IDF) objects in the plugin files, but also holds editable information with regards to:

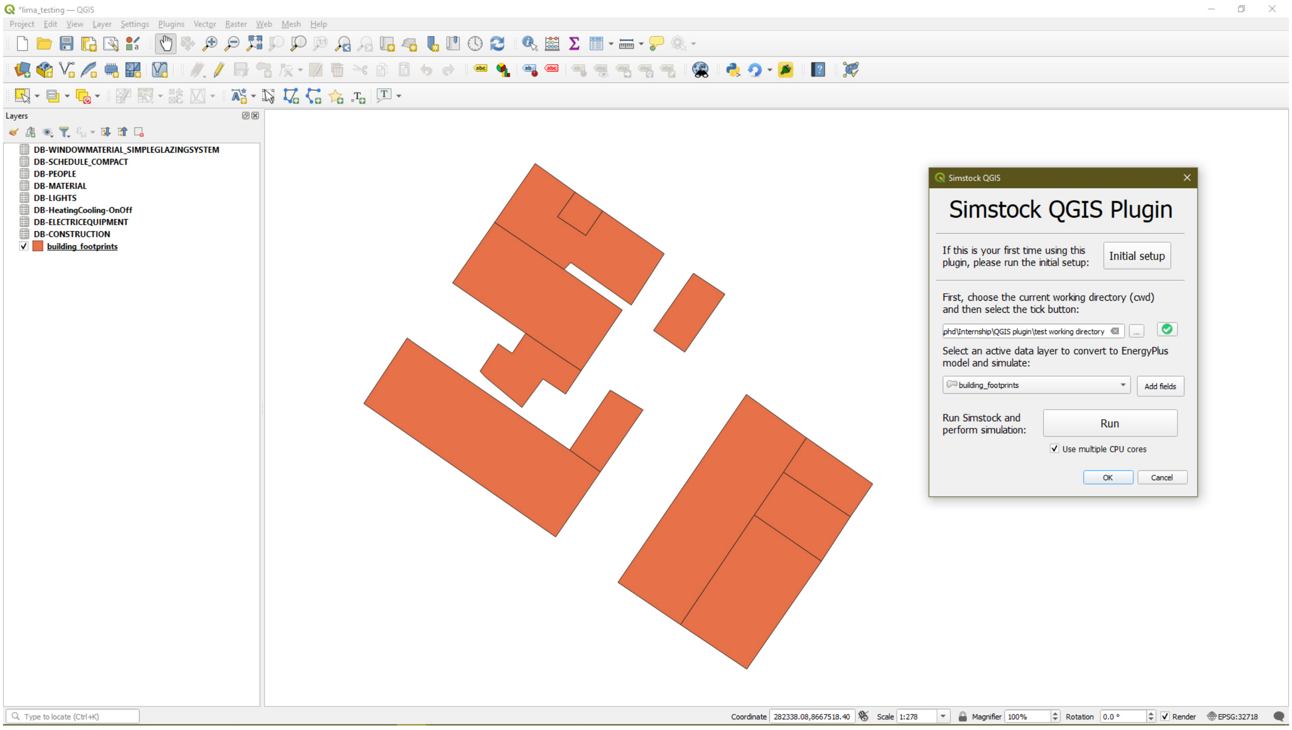
- Construction layers
- Construction materials
- Heating and cooling systems
- Internal gains (people, lights, equipment)
- Occupancy schedules

The plugin, pictured in Figure 2, loads the database into the QGIS session when the user sets the current working directory. The database is packaged into a single geopackage file and placed in the working directory. This contains a series of vector layers with no geometry, with each layer corresponding to a different EnergyPlus object class. The user can interact with these layers in order to specify the model inputs for a given use case, by viewing, editing and exporting the database as necessary.

Computational method (Simstock)

Once the input data have been finalised, Simstock is called to create the EnergyPlus models. Firstly, the script proceeds with pre-processing of the geometry data, which includes checking for invalid polygons, intersections, duplicate coordinates and so on. Based on these tests, Simstock automatically rectifies these problems where possible. Touching polygons are identified and analysed in order to inform which walls are exposed, and which form partitions between two buildings.

Once the pre-processing is complete, the next stage of the process creates the EnergyPlus models. SimStock combines the input data and the pre-processed geometry to create all required model objects. Each component of the resulting building models is appropriately named with reference to the polygon/zone to which it belongs. The pre-processed geometry data and derived information is used to create building surfaces. Windows are placed on the walls with proportions according to the specified window-to-wall ratio.



DB-WINDOWMATERIAL_SIMPLEGLAZINGSYSTEM
DB-SCHEDULE_COMPACT
DB-PEOPLE
DB-MATERIAL
DB-LIGHTS
DB-HeatingCooling-OnOff
DB-ELECTRICEQUIPMENT
DB-CONSTRUCTION
☑ building_footprints

Simstock QGIS Plugin

If this is your first time using this plugin, please run the initial setup:

First, choose the current working directory (cwd) and then select the tick button:

phd\Internship\QGIS plugin\test working directory

Select an active data layer to convert to EnergyPlus model and simulate:

building_footprints

Run Simstock and perform simulation:

☑ Use multiple CPU cores

Coordinate 282338.08,8667518.40 Scale 1:278 Magnifier 100% Rotation 0.0 ° ☑ Render EPSG:32718

Figure 2: Screenshot of the QGIS interface using the SimStock plugin in Windows 10 for a set of buildings in a block arrangement, with the database layers on the left hand side of the QGIS interface.

One thermal zone is created per floor of each building. All of the data for materials, constructions, schedules and internal gains are sourced from the database layers and assigned accordingly. The heating and cooling variables at this stage remain fixed as ideal loads. The research team will work towards enabling full functionality and editing of all possible configurations in the coming future. Finally, shading blocks are created according to the input data. Most model objects are created using Eppy Philip (2022), a Python package which facilitates the interface with EnergyPlus IDF files.

When the models are finalised, the plugin internally calls EnergyPlus to perform the dynamic thermal simulations, since it is packaged as part of the Simstock plugin for QGIS.

Outputs

After the IDF files are simulated in EnergyPlus, the raw results are output into the user specified working directory. These results are read by the plugin. The selected input layer is then duplicated and the results are added to the attribute table of this new layer. Results are reported at the floor level. Since the results are loaded as feature attributes, these can be easily visualised using pre-existing tools in QGIS or other visualisation plugins.

Results Case Study examples

Results from the initial testing include the outputs and analyses of two case studies. One in Lima, Peru and one in Ahmedabad, India. The case study in Lima contains three blocks of buildings in the informal district of El Agustino, which has been growing continuously since the 1950s and now represents a type of consolidated informal settlement, with self-constructed houses. For this study area, the research team had access to data from a drone survey as well as from local experts. The building geometry of the 165 buildings (presented in Figure 3) in these three blocks in El Agustino was estimated using data from the drone survey. The footprints of the buddings were manually hand-drawn in QGIS, shown in Figure 4, and the heights per floor were taken as 3m. The heights of the buildings were calculated using a Digital Elevation Model (DEM) that was produced in QGIS, making further use of the data captured from

Figure 3: Drone survey produced image in the study area of El Agustino, Lima, Peru

Figure 4: Building footprints of the study area in El Agustino, Lima, Peru

Figure 5: The extruded polygons in the study area of El Agustino, Lima, Peru

the drone. For this, the Mean Sea Level (MSL) in El Agustino was taken as 211m. Figure 5 shows the extruded polygons of the 165 buildings, in the QGIS environment.

The fabric of the buildings was largely estimated based on the local knowledge from experts in the Pontifical Catholic University of Peru (PUCP), in Lima, as well as the inspection of the drone images. The construction of external walls was set as uninsulated brick with cement and was assumed as uniform across all buildings in the study area. The same uniformity was applied to the window-to-wall ratio (40%) and to the ground floor type (solid concrete floor slab). Two types of roof assigned to the buildings, steel corrugated sheet or a lightened reinforced concrete ceiling. The HVAC systems and controls in these low-income houses in El Agustino are very rarely present, and therefore, the heating and cooling loads during the UBEM simulations were completely switched off. In terms of internal gains and occupancy schedules, these were also applied uniformly for all building thermal zones.

Once all input data were completed, the SimStock plugin created the models and initiated the dynamic thermal simulations of the 165 buildings in EnergyPlus. The completion of the simulations took about 8 minutes on a Windows 10 laptop with an i7 Intel Core processor at 3.00GHz and 16GB RAM. An initial post-processing of the results focused on the maximum indoor temperatures per thermal zone in all buildings and the results were pushed back to QGIS for visualisation. Figure 6 shows the two-dimensional representation of the maximum internal temperature ranges per floor, in the three blocks of buildings simulated. As the number of floor rises, there are fewer buildings that have that many floors, hence by floor 7 (F7), there are only a handful. From the graph, it can be seen that the higher floors present a higher proportion of buildings with higher temperatures.

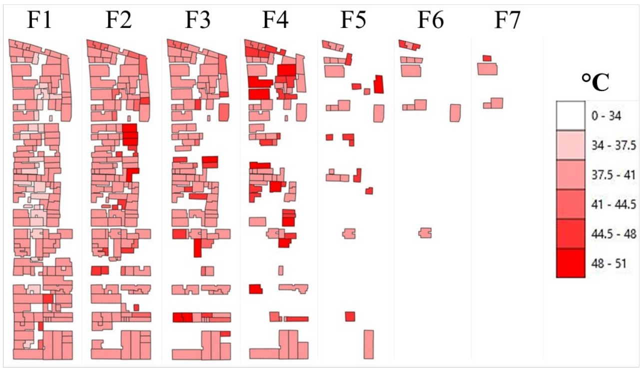


Figure 6: 2D Visualisation of results. Maximum indoor temperature per floor for each building in the study area of El Agustino, Lima, Peru

In Ahmedabad, the case study area comprised of 263 buildings in the residential ward of Bodakdev, which has been growing continuously since the 1990s. The geometry of these buildings, presented in 2D Figure7 and in 3D in Figure8, was estimated using data from a drone survey.

The buildings' fabric was estimated based on the inspection of the drone images as well as the knowledge of local experts at CEPT university. The buildings consist of two types of construction, low rise buildings (mainly individual bungalows) and high rise buildings (mainly framed structures of more than two storeys). The external walls of the low rise buildings were set as uninsulated brick with cement mortar while those of the high rise buildings as reinforced concrete, with brick and mortar as non-bearing walls. The area of the selected residential buildings ranges from 40 m^2 to 700 m^2. The window-to-wall ratio was fixed at 30%, while the roof and ground floor type were selected as concrete and bitumen respectively. In terms of internal gains, and occupancy schedules, these were also applied uniformly for all building thermal zones.

Figure 7: Building footprints of the study area of Bodakdev in Ahmedabad, India

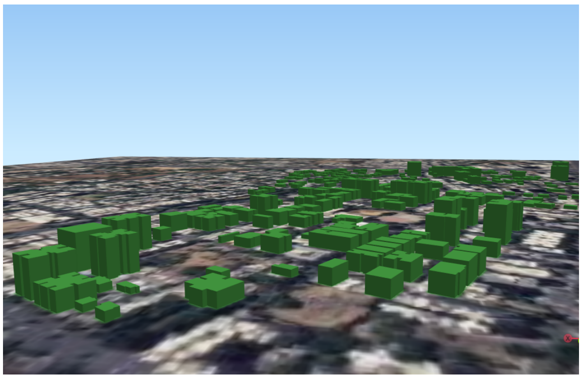


Figure 8: The extruded polygons in the study area of Bodakdev in Ahmedabad, India

Follwing the specification of the input data, SimStock was called to create the models and send the IDF for simulation. The results from the EnergyPlus simulations were pushed back to QGIS and the initial post-processing focused on the electricity demand of the buildings. Figure9 shows the three-dimensional representation of the annual electricity demand of all 263 buildings. A retrofit scenario was planned at this stage, to be able to showcase the visual representation of the differences in electricity demand pre- and post-retrofit, however time restrictions did not allow for this task to be completed on time for the submission of this paper.

Further Work

The SimStock plugin for QGIS has been in operation and has reached a stage where dynamic thermal simulations can be run in EnergyPlus successfully from the QGIS environment and results automatically retrieved. Although this has paved the way for a number of developments, such as creating UBEMs in cities in the Global South and also producing educational material and delivering post-graduate taught courses on urban scale tools in three different continents, there is still plenty of room for improvements and additional functionality. The research team are next planning to proceed with the following developments:

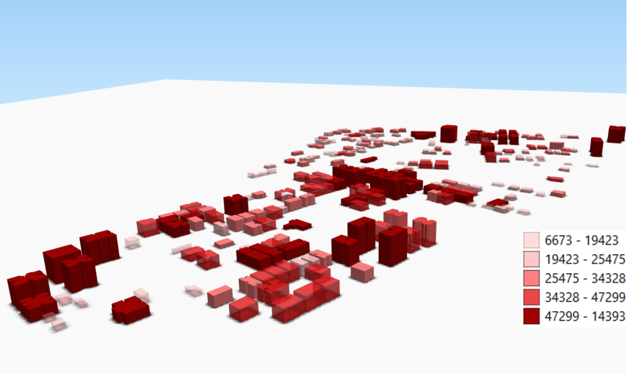


Figure 9: 3D Visualisation of results. Electricity annual demand (kWh) of all buildings in the study area of Bodakdev in Ahmedabad, India

- Ability to select and retrieve any available EnergyPlus outputs and to manipulate these if required
- Improvements to the database:
    - Database manager: checks for duplicates, misspellings and validity of objects
    - Collaborative database: hosted online with the ability for users to download, view and contribute to the database
- The ability to split each floor into separate thermal zones with different uses
- Include definitions of HVAC systems
- Move from a flat-Earth approach to one which supports uneven topography

Conclusion

This paper presented the development of a free and open access plugin for Urban Building Energy Modelling in a geospatial tool. The SimStock plugin for QGIS was demonstrated in terms of input data requirements, the computational method that sits at the heart of the calculations and the output formats. Two case studies were also presented, one in Lima, Peru and one in Ahmedabad, India. These allowed practical insights of the tool to be explored and explained, with the results exhibiting some of the visualisation advantages of utilising a geospatial platform, such as QGIS.

The SimStock plugin presents a number of advantages compared to other available tools. First and foremost it is freely available, contributing to open science by lowering barriers to powerful research methods, tools and outputs. Secondly, it actively supports increased open access by being able to run in multiple operating systems. Additionally, it has simple input data format requirements, increasing the prospects of reproducibility. Its ability to operate with different levels of detail in terms of input data requirements, from very basic to very detailed, allows it to overcome a significant barrier to access for UBEMs in the Global South. Moreover, it is based on one of the most established and advanced tools, for dynamic building energy simulations, EnergyPlus, enhancing its credibility substantially. While, operating through a single interface within the free and open source software QGIS, allows for visualisation and analysis of outputs and integration with other forms of urban data. Lastly, it does not require advanced computing skills for using it, potentially placing it at the heart of educational material across continents.

The aforementioned advantages support the usability of the SimStock plugin for QGIS by an increasing amount of different groups and stakeholders, as urban building energy modelling becomes important in developing healthy, energy efficient and decarbonised cities.

Future work is already underway to incorporate a number of new and improved functionalities to the SimStock plugin, allowing it to become more advanced and establish itself as a complete platform for dynamic thermal urban building energy modelling.

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]. The support of the Economic and Social Research Council (ESRC) is gratefully acknowledged.

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