Evaluating the Influence of Program Type Building Parameters on UBEM: A Case Study for the Residential Stock in Nottingham, UK

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ABSTRACT

In the midst of rising concern about the implications of climate change, the European Union and the United Kingdom appears to be on the verge of establishing policies to reduce greenhouse gas emissions. The urban building energy models could inform energy analyzers and decision makers for the future results that specific comprehensive energy refurbishment strategies and energy supply infrastructure changes might have. Nonetheless, the data challenges that emerge are various. The lack of data availability and reliability, the data computing issue and data privacy are, only, some of the challenges of building energy modelling, which are intensified in urban scale. Therefore, the investigation of the influence of building parameters on the energy demand results is deemed necessary, in order both to understand the minimum data requirements for urban energy modelling, and the impact of them before the design phase for the new constructions. Therefore, this Paper's intention is to inform stakeholders from energy analysts to data capture companies, about the influential building parameters, as regards to the Program Type, such as the infiltration, the domestic hot water and the ventilation. An UBEM physics-based approach, for the estimation of the annual energy demand, is implemented with the use of Grasshopper software, and the visualization of the results is done with the QGIS software. The case study is in Nottingham city, in UK, and the energy demand for the whole year of the dwelling stock is estimated. Then, a sensitivity analysis for the influence of the Program Type building parameters is presented. The results have shown that the most impactful parameter among the three under-tested is the infiltration (airtightness) of a dwelling.

INTRODUCTION

According to the European Environment Agency (EEA), a change in regards to human activities in daily life is urgently required to address climate change issues, avoid further deterioration, and ensure future prosperity [1]. The Third United States National Climate Assessment defines the term "climate change" as long-term changes in precipitation, temperature, and all other climatic factors, which means that future climate scenarios are characterized by extreme weather events [2]. Unless significant steps are taken to restrain greenhouse gas (GHG) emissions, the current forecasts state that the world's temperature will rise by 2.5 °C (36.5 °F) to 4.5 °C (40.1 °F) by 2100, leading to the highest temperature records in the 21st century [3]. Therefore, the global warming limit of 1.5 °C (34.7 °F) to 2 °C (35.6 °F), would become impractical if GHG emissions are not decreased significantly and promptly [4].

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The United Nations Intergovernmental Panel on Climate Change claimed that the energy supply, industry and buildings, transportation, land use and agriculture are, essentially, the reasons for the large growth of greenhouse gas emissions, which has been linked to the built environment [5,6]. Specifically, a recent report from IEA, in 2022, has pointed out that buildings are responsible for 30% of the worldwide final energy consumption, and 33% of its energy-related greenhouse gas emissions [7]. Moreover, by 2050, the population of the world would have topped 10 billion and the 2/3 of it will be living in urban areas, resulting to the construction of new buildings and the renovation of the existing ones, with purpose to make existing cities an adequate and habitable environment [8,9]. Therefore, to slowdown the pace of climate change, policymakers are establishing energy and greenhouse gas emission reduction plans and adopting mitigation strategies, at national levels [10].

Building sustainability in Europe is addressed through the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED) [11]. In addition, as the host of COP26, which finished in October 2021, the United Kingdom was the first large nation to adopt net-zero rules and has been at the vanguard of securing international action to mitigate the effects of climate change [12]. Moreover, over the past ten years, several pieces of legislation have been passed at the national and local levels throughout Europe to acknowledge EU mandates on energy efficiency and to advance energy-saving practises in each country [13,14]. Hence, in order policymakers to be able to establish regulations for tackling the climate change, the appropriate information regarding the energy performance of the building stock should be given through Urban Building Energy Modelling (UBEM).

As it has been pointed out in the research studies of Kim & Suh, and Sarkar & Bardhan, one of the most important techniques for saving energy in buildings is the correct design of building parameters [15,16]. Therefore, by informing city-planners and government with the most influential parameters in city scale, it helps them find the most appropriate solutions and suggestions for energy efficiency measurements. In a past research study, it has been pointed out that the occupancy of a building and its preliminary design, plays one of the most important roles in its energy performance [17]. Another study has shown that the impactful building parameters seem to have a variation through the seasons of the year, and the ranking of them is changing depending on weather events [18]. Many other studies have checked the insulation thickness of individual buildings as well, such the research from Evin & Ucar, that has concluded that its influence has a seasonal variation [19]. Moreover, in another study, it has been found out that the infiltration of the building envelope has a big impact on its energy consumption [20].

Apart from the above, the data challenges that occur from the upgrade of individual building energy modelling to the urban scale energy modelling are numerous, with the most common to be the data availability. Other challenges that occur are the data reliability, the data computing issue and the data privacy. Hence, defining the most impactful building parameters could be useful not only for the policymakers in order to construct regulation to reach the environmental goals, but also for data capture companies that are necessary in order to provide energy analysers with the essential data for urban building energy modelling.

From all the above, selecting the right design of the building parameters can help to the energy demand reduction for the climate change mitigation and adaptation of the building stock. However, none of the above research studies has investigated the percentage difference of the building parameters in the energy demand, and none of them has found out the impact on residential stock at district scale. Therefore, at this paper an UBEM physics-based approach is implemented, in order to estimate the percentage difference in the urban energy demand for 1% change in the building design parameters. More specifically, as an initial step, three Program Type parameters were chosen, namely the infiltration, the domestic hot water and the ventilation for the residential stock, and more building design parameters are planned to be investigated in future analysis. The purpose of this research is to give information regarding the Program Type building parameters that should be given emphasis both in the design stage of a highly efficient residential stock and in the stage of data acquisition of the existed building stock where renovation is needed.

METHODOLOGY

The proposed methodological approach was implemented in two neighborhoods in Nottingham city, in UK, in order to estimate the influence of the Program Type parameters, namely the infiltration (airtightness), the Domestic Hot Water (DHW) flow rate and the ventilation (Air Change Rate (ACR)) to the energy demand at district scale.

The first step was the construction of the energy model for Urban Building Energy Modelling (UBEM). After that, the gathering of the data and the construction of the necessary dataset, for Nottingham city, were done, in order to import the completed dataset to the QGIS platform, which allows to choose the two different case studies. After exporting the two different datasets for the case studies, they were imported to the energy model, in order to provide it with both geospatial and non-geospatial building data. The following step was to run the energy model under different scenarios, related to the Program Type parameters, for the evaluation of the hourly energy demand of each building in both case study areas. Then, the results were processed through Python programming language, in order to acquire the district energy demand percentage differences for 1% change of each under-test parameter. Finally, the post-processed results were visualized with QGIS in maps and graphs created through Python. In Figure 1, the methodological diagram is illustrated, and in the next sections is explained.

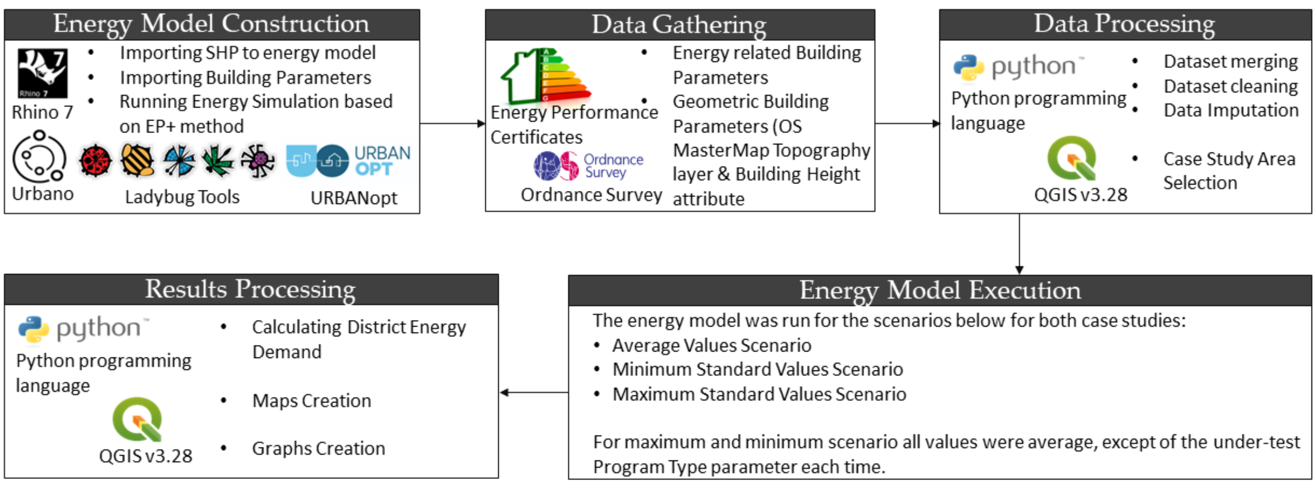

Figure 1 Methodological Diagram.

Energy Model Construction

The energy model was constructed with the use of Rhino7. Particularly, in Grasshopper the case study area is imported in the shapefile format, in order to provide the geographic and geometric building characteristics, such as the building footprint and building height, that are gathered from OS MasterMap Topography layer and Building Height Attribute, respectively. Then, the Program Type parameters are set, which are the occupancy, the lighting, the electrical equipment, the hot water service, the ventilation, the infiltration and the setpoint. The information for them is taken from ASHRAE standards, UK standards and background knowledge. Following that is the assigning of the Window-to-Wall ratio, which is defined from past research studies and standards, and after having all the necessary building data, the climate data is imported in EPW format, in order to run the energy simulations.

Data Gathering

The data that was used for the implementation of the methodology consists of geospatial data, geometric and energy related building data and weather data. The geospatial data are gathered from OS MasterMap Topography layer with the polygon of each building, the geometric building data from OS Mastermap and Building Height attribute, the energy related data from Energy Performance Certificates (EPCs), and the weather data from OneBuilding in Energy Plus Weather (EPW) file format. Table 1 shows the data providers, sources and formats.

Table 1. Datasets

Dataset	Provider	Source	Format
OS MasterMap Topography layer	Ordnance Survey	Digimap, EDINA	GPKG
OS MasterMap Building Height attribute	Ordnance Survey	Digimap, EDINA	CSV
OS AddressBase Plus	Ordnance Survey	Ordnance Survey	CSV
OS Boundary Line	Ordnance Survey	Digimap, EDINA	SHP
Energy Performance Certificates	Open Data Communities	epc.opendatacommunities.org	CSV

Data Processing

The data processing was conducted with Python programming language through Jupyter notebook and Anaconda. The datasets were merged, cleaned and a statistical approach was used in order to input the building age for buildings with unknown age bands from EPCs. Then, through QGIS platform, two different neighborhoods in Nottingham were chosen, one case study area that the majority of buildings had a known age band, and one case study area that most of the buildings had unknown building age, that has been imported though the statistical approach. In the following subsection the case studies are described.

Case Study Areas

Both areas that were chosen as case studies are located in Nottingham city, in the UK, and are characterized as urban areas. The visualization of them, through Rhino7, is presented in Figure 2. Both Case Study Areas are in North Nottingham. More particularly, the Case Study Area 1 (CSA1) is located in Bestwood, and the Case Study Area 2 (CSA2) is located in Bilborough. The difference between them is that the CSA1 consists of buildings that most of them owned by a known age band in EPC dataset, whereas in CSA2 all the buildings required building age imputation via a statistical approach. Finally, both CSA1 and CSA2 consist of 300 buildings, approximately.

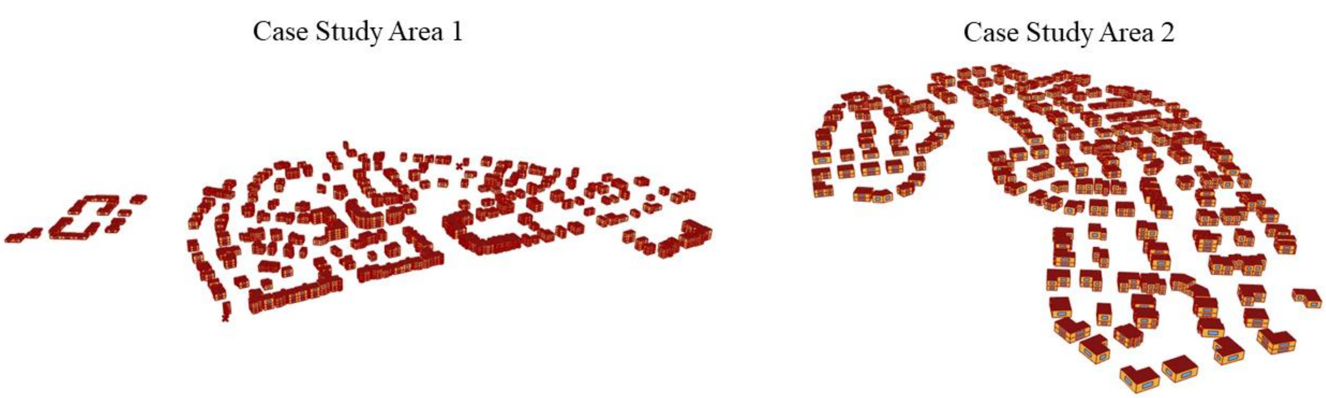

Figure 2 Case Study Areas – Honeybee Model visualization in Rhino7.

Energy Model Execution

The energy model was executed six times for each case study in total, under different scenarios. The first scenario is the baseline, where all the building parameters are taken from energy standards, averages and literature review. After that, three different Program Type building parameters were tested. The first parameter is the infiltration (airtightness), namely whether the building is leaky or tight, or has the standard average value of airtightness. The second parameter is the domestic hot water flow rate, and the third parameter is the ventilation, namely the air change rate. Therefore, for each parameter, the model was run for its minimum standard and maximum standard.

Results Processing

After obtaining the results from the energy model, the findings for each building were imported to Jupyter notebook, and further analysis was done, in order to aggregate the results for the district energy demand, calculate the percentage difference of the energy demand for 1% change of each under-test Program Type parameter, both in district and building scale, and create the shapefiles for the visualization and the graphs for the comparison of the results.

RESULTS & DISCUSSION

The objective of this paper is to estimate the influence of the Program Type building parameters, particularly, the impact of infiltration, domestic hot water flow rate and air change rate, on the building energy demand at individual and district scale for the residential building stock. The findings of the UBEM physics-based approach, that was used for the estimation of the annual energy demand and the percentage difference for 1% change of the Program Type parameters, of the two case studies, is presented in the following section.

Energy Demand Graphs

After running the model for each scenario and each case study area, from Rhino7, both the energy results in CSV files for each building, and district energy demand graphs, were gathered. For the CSA2 baseline scenario, where the values of the Program Type parameters were obtained from averages and standards, the results are shown below, as an example of the material that the energy model provides.

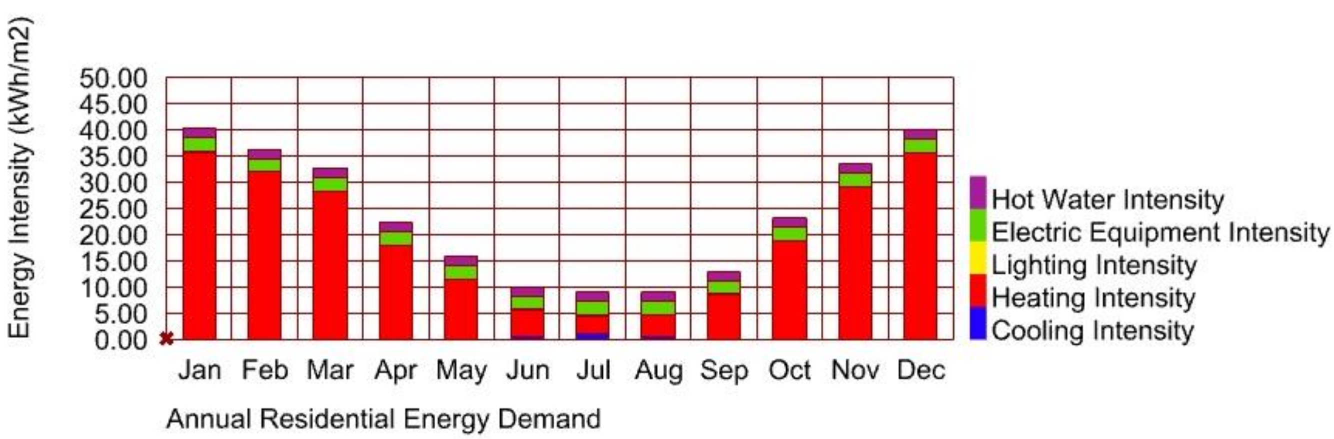

Figure 3 An example of the District Annual Residential Energy Demand graph that is obtained through the energy model in Rhino – CSA2 results for the baseline scenario (1 kWh/m² = 0.3 kBtu/sf).

The graph above shows the energy demand of the dwellings in Bilborough (CSA2), for each month of a year and for the baseline scenario. As it can be seen, the findings are reasonable according to the pattern that it is expected for the energy demand in terms of seasonal variation. However, for the presiced and absolute energy results further research for validation is needed. Nonetheless, this is not the objective of this research study, as the percentage difference is aimed to be estimated according to the 1% of the building parameters.

Annual Residential Building Energy Demand Percentage Difference Maps

At this section the main focus of this research is presented. After processing the energy results that were gathered from the energy model, with Python programming language, the energy demand percentage change for 1% change in the three under-test Program Type building parameters has been calculated and exported in shapefile format, for both case studies, in order to be visualized with QGIS platform. In Figure 4, the influence of the infiltration (airtightness) of the buildings, the DHW flow rate and the ventilation (ACR), are shown for CSA1.

Figure 4 Impact on Annual Residential Building Energy Demand for 1% change in the under-test Program Type building parameters in CSA1.

As it can be seen, the airtightness (infiltration) of a building plays a significant role in the final energy demand of the year, fluctuating between 0.16% and 0.72% energy demand percentage change for 1% change of the airtightness. Especially, by comparing the influence of the 1% change of the domestic hot water air flow that gives the lowest percentage change in the energy demand, which is much lower, equal to the range of 0.03-0.23% for each dwelling. According to the ventilation (air change rate), it is shown that there is a higher percentage difference in the energy demand (0.16%-0.46%) than the one from the change of the DHW flow rate, but not as high as for the airtightness. Finally, one thing that it can be observed from the maps in Figure 4 is that the area of the building, whether is large or smaller, could contribute to the impact of ventilation on the energy demand, but further research is needed to state this.

A similar image of the situation is given from CSA2, as it is obvious from Figure 5. The most influential Program Type parameter remains the infiltration with a range of 0.43% to 0.61% difference of the energy demand for 1% change in infiltration value. Then, the ventilation follows with a percentage difference band of 0.19-0.37%, and last is the DHW flow rate that fluctuates between 0.04 and 0.18%. Nonetheless, for this CSA, the contribution of the dwelling area to the air change rate influence cannot be estimated, as the specific CSA is characterized by homogeneity in terms of building footprint. Finally, from both case study areas there is no doubt that whether a building is leaky or tight plays the most significant role in the final energy demand among the three under-test Program Type building parameters.

Figure 5 Impact on Annual Residential Building Energy Demand for 1% change in the under-test Program Type building parameters in CSA2.

Annual Residential District Energy Demand Percentage Difference Graph

Finally, it has been deemed necessary to estimate the influence of the three under-test Program Type parameters in the energy demand of a whole district. Therefore, for both case study areas the total energy demand has been estimated for all scenarios and then, the percentage change for 1% change of all three building parameters has been estimated, in order to compare their influence in Urban Building Energy Modelling.

As it can be seen, in Figure 6, the results that were gathered from the above maps are aligned to the findings for the whole district. For both case study areas, infiltration remains the most impactful Program Type parameter, with approximately 0.5% influence in district energy demand for 1% infiltration change, followed by the air change rate (0.3%) and third in the ranking is the DHW flow rate (0.2%).

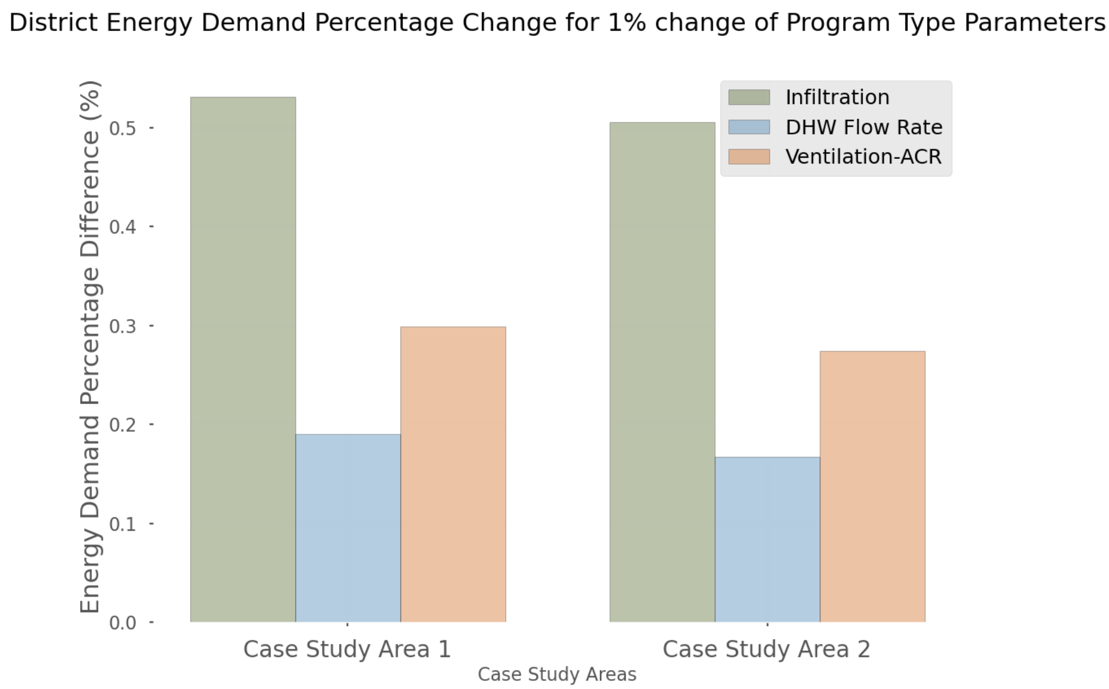

Figure 6 Impact on Annual Residential District Energy Demand for 1% change in the under-test Program Type building parameters in CSA1 and CSA2.

CONCLUSION

This paper aimed for the investigation of the most influential Program Type parameters in building energy demand at city scale. The impact of the infiltration (airtightness), the domestic hot water flow rate and the ventilation (air change rate) in the estimation of the district energy demand was calculated through an UBEM physics-based approach, by constructing an energy model in Rhino7 and Grasshopper, which uses EnergyPlus simulations in the background. The analysis was conducted in two neighborhoods in Nottingham, UK, in order to allow for the comparison of the district energy demand results. The findings show that the most impactful Program Type building parameter among the three that were tested is the airtightness of the dwellings, which is aligned with the findings of the research study from Qin & Pan [20]. The air change rate is ranked second, and last one is the DHW flow rate. Future work points toward the investigation of the influence of other building parameters to the energy demand at district scale, such as the construction materials and the Window to Wall ration.

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LIST OF ABBREVIATIONS

ACR = Air Change Rate
COP26 = Conference of the Parties (COP26 was the 2021 United Nations climate change conference.)
CSA = Case Study Area
CSV = Comma-Separated Values
DHW = Domestic Hot Water
EEA = European Environment Agency
EED = Energy Efficiency Directive
EPBD = Energy Performance of Buildings Directive
EPC = Energy Performance Certificate
EU = European Union
GHG = Greenhouse Gases
IEA = International Energy Agency
OS = Ordnance Survey
UBEM = Urban Building Energy Modelling
UK = United Kingdom

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