The Importance of Occupancy and Energy Use Patterns on Predicting Building Energy Performance: A Case Study of a Residential Building in London

Sahar Zahiri[1], Heba Elsharkawy[1], Wei Shi[1]
[1]Department of Architecture and Visual Arts, University of East London, London, United Kingdom

Abstract

This paper studies a building energy performance of a council housing tower block in London, which was found to consume significant energy for heating. The aim of this study is to explore the impact of the occupancy and heating energy use schedules of the building units in predicting the building performance using DesignBuilder (DB) dynamic simulation tool. This study adopts a quantitative research design based on a survey questionnaire, and dynamic simulation modelling and analysis. The predicted building performance using the dominant occupancy and energy use profiles was compared against the simulation outputs using the approved benchmark methodologies. The results show that the building's physical issues including damp and mould, as well as the occupants' patterns of operating their homes have a considerable impact on the heating energy use in the winter season and demonstrate the importance of incorporating the exemplary occupancy and energy use schedules into the building simulation tools to predict feasible building performance.

Introduction

Building energy consumption accounts for more than 40% of the global energy use (BEIS, 2017; Song *et al.*, 2017). In addition, the occupants' energy consumption patterns play a significant role in the intensity of the energy used in buildings (Rouleau et al., 2018). This can cause the discrepancies between the predicted energy consumptions in comparison to the actual energy use (Heidarinejad *et al.*, 2017). In fact, the occupancy schedules associated with the energy consumption patterns have a considerable impact on evaluating and predicting building performance using dynamic building simulation software. Using the representative occupancy and energy use patterns may yield reliable simulation outputs and help to reduce the gap between the predicted and the actual building performance. However, there is a lack of consensus on recommended methodologies to input occupants' energy consumption behaviour in the simulation tools (Yan *et al.*, 2017).

This research assesses building energy performance of a high-rise residential block in London, which uses significant energy for heating due to its inefficient building envelope. The aim of this study is to explore the impact of several potential occupancy and energy use schedules on predicting building energy performance using DesignBuilder (DB) simulation tool. This study compares building simulation results using different profiles based on the actual dominant energy and occupancy patterns of the case study building in comparison to the predicted results using standardised methodologies.

The effect of occupants' energy use behaviour on building performance

One of the main factors of uncertainty in predicting the building performance is the occupancy and the energy use schedules associated with the energy consumption (University of Southampton, 2016; Stazi, Naspi and D'Orazio, 2017). The energy consumption level highly associate with the energy use patterns and the occupants' presence within the buildings (Ahmed *et al.*, 2017). In addition, mechanical cooling and heating systems dominate the buildings energy consumption levels in domestic building sector, while lighting and domestic hot water (DHW) contribute next (ADEME and Agency, 2015). Studies also assert that the occupants' energy use behaviour and their socio-economic background may have a significant impact on the intensity of energy used in buildings (Stazi, Naspi and D'Orazio, 2017).

To optimise the building energy performance, it is necessary to predict the feasible energy use. However, the lack of understanding the occupants' impact on the total buildings energy consumption can result in a gap between the measured and the predicted building performance (Chang and Hong, 2013; Ahmed *et al.*, 2017). According to Song et al. (2017), there are a few barriers to predict the building energy performance using occupants' energy use data. These barriers include occupants' diversity and the correlation with the energy use relating to the different energy consumption behaviour. There is also a lack of consensus on approved methodologies of occupants' energy use patterns to be incorporated into building simulation tools (EBC, 2016; Yan *et al.*, 2017).

Aerts et al. (2014) studied the effect of occupancy schedules and the users' behaviour on the energy consumption of the building to define an approach for building simulation tools. The occupancy patterns of more than 3400 Belgian households were studied considering the details activities of around 6500 occupants. Seven occupancy profiles in three states were also defined to be used in the simulation analysis and modelling. These profiles include "home and awake", "sleeping" and "absent" states but it was found that these schedules are simple to be applied to the simulation modelling, as they are very general and there is a lack of information regarding the interaction between the occupants and the internal spaces. Ahmed et al. (2017) also studied the development of the occupancy, lighting, appliances schedules and input data for new energy calculation methods. The identified profiles were applied to 10 different building types and could be easily applied to the simulation tools. In this study, the occupants' hourly patterns were defined based on the culture and their local background. The study showed that the average and constant general schedules can not predict the actual energy required and highlighted the importance of realistic hourly schedule for different building sectors. Song et al. (2017) also examined the effect of occupancy related behaviours on predicting buildings energy performance. A data mining based prediction model was created to adapt building thermal behaviour and to select representative end-user groups. The model gave more insight into the daily energy peak demand and daily energy use patterns. It was found that identifying the occupancy related behaviours considerably help in predicting reliable building energy performance.

Moreover, a methodological framework for occupants behaviour study has been launched (Annex 66) aiming to set up a standard occupant behaviour definition platform, provide a quantitative simulation methodology to model behaviour in indoor environments and understand the impact of behaviour on building energy consumption (Yan *et. al*, 2017). It consists of application guidelines to help in building design operation and policymaking using interdisciplinary approaches to reduce energy use in buildings and improve the occupants' indoor comfort. It also shows the importance of integrating the occupants' behaviour with the building lifecycle (Yan *et. al*, 2017). Considering the use of the actual and prominent occupancy and energy use patterns of the buildings in the thermal simulation model can reduce the gap between the predicted and the actual building performance.

Methodology

The aim of this research is to examine the impact of different occupancy and heating energy use patterns on predicting the energy consumption of a residential tower block in London Borough of Newham (LBN) during the winter season and select the representative profiles to be incorporated into DB simulation tools for energy simulation modelling and analysis.

The case study is a 22-storey high-rise building constructed in 1966 and consists of 108 one-bedroom and two-bedroom flats (Figure 1). The structure is in-situ reinforced concrete frame construction with floor slabs spanning between shear walls, and pre-cast concrete panels covering the flank wall. Externally the building envelope is fitted with asbestos cement over-cladding panels. All flats have double-glazed windows with UPVC frames. The internal partition walls consist of concrete blocks of 100 mm thickness and the external walls include external over-cladding of 9 mm thickness, 80 mm air gap, 200 mm pre-cast concrete panels and 20 mm internal wall insulation boards and plaster finishes. In addition, internal floors consist of 150 mm reinforced concrete slabs as well as wall and ceiling plaster finishes. Heating is provided by natural gas-fired hot water boilers and there are also two extractor fans in each flat; one in the kitchen and another in the bathroom.

(a) (b)

Figure 1: Case study (a) and the typical floor plan (b) (Newham Council, 2007)

The case study has the significant damp, mould and condensation problems. In order to identify the problematic areas within the tower block, Newham Council conducted a water ingress survey in 2016 (Newham Council, 2016). It was found that at least one fourth of the properties experienced serious damp, mould and condensation issues. To identify the cause of damp penetration, the internal damp survey was conducted in two sample flats (Flat A and Flat B) using a damp meter. It was found that the jet washing of external over-cladding in 2012 may have damaged the over-cladding and as a result, the moisture would have transferred through gaps into the building and caused dampness issues (Medhurst, Turnham and Partners, 2016). An structured interview and a field monitoring of indoor air temperature and relative humidity levels (RH) were also performed in the sample flats during the winter season from Dec 2016 until March 2017 in order to evaluate the building performance (Zahiri and Elsharkawy, 2017). It was found that although the indoor air temperature and RH levels were normally within the comfort zone in the occupied rooms, the occupants were not satisfied from the indoor thermal comfort and they used more heating energy than required in the cold season to reduce the effect of the damp and condensation. Newham Council has planned for the energy efficient and the cost effective retrofit in the short term.

The research methodology is based on quantitative research methods; mainly a questionnaire-based survey on the occupants' energy use behaviour, as well as building simulation analysis. A questionnaire-based survey was conducted in autumn 2016 to gain more insight into the occupants' patterns of operating their homes. A dynamic building simulation modelling using the dominant occupancy and energy use patterns was also undertaken to identify the impact of different occupancy schedules on predicting the building energy consumption in the winter season. The predicted energy consumption using the representative energy-use scenarios was compared against the standard occupancy and energy use methodologies (SAP 2012 and TM 59). SAP 2012 is the UK government's procedure developed for the energy rating of dwellings (DECC, 2014) while CIBSE TM 59 is a newly developed guideline for the assessment of overheating risk in new and refurbished dwellings (CIBSE, 2017). As overheating risk will form one of the main concerns of the study for retrofitting and the next stage of the study focuses on the whole year, TM59 occupancy patterns along with SAP 2012 heating patterns were applied to the DB model. The results of this study will help to select the most reliable occupancy and energy use patterns to predict the building performance and support the Newham Council's retrofit plan.

Results and Discussion

Questionnaire-based Survey

A questionnaire-based survey on the occupants' energy use behaviour was conducted to get more insight into the occupants' patterns of operating their homes in the case study tower block during the cold season. 108 questionnaires were distributed to all the properties and 37 responses were received for the dwellings (30% response rate, which is acceptable). The results of the survey show that around 32% of the occupants are aged below 19 and around 50% of them are aged between 19 and 44, while the rest are older generation including 65 years old occupants (Figure 2). According to the survey results, 31% of the properties are occupied by a single occupant (low occupancy) while 31% of the properties are occupied by four to seven people (moderate to high occupancy).

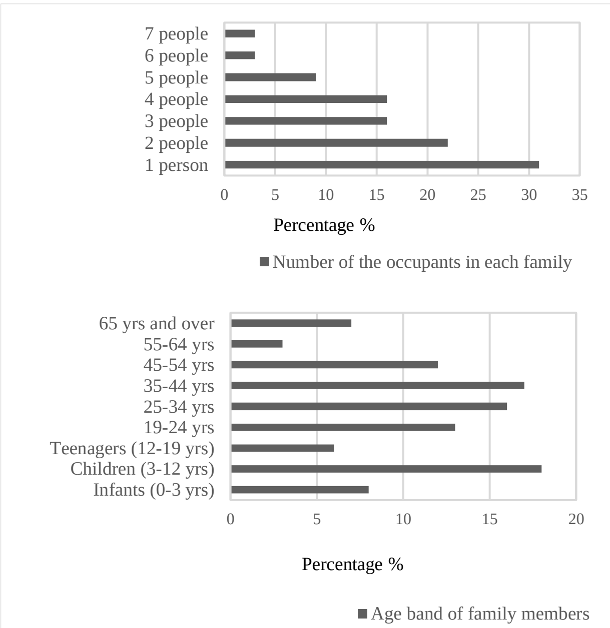

Figure 2: The number of the occupants in each family as well as their age band in the surveyed flats

The results also demonstrate that as the occupants' age band increases, they tend to use less heating in the winter season, while the households with more number of children tend to spend more on energy bills (Table 1). Table 1 shows that the heating energy use in the winter season negatively correlates with the age of the occupants but strongly correlated with the members of the households with children. This is mostly due to provide better indoor thermal environment for the children. The occupancy schedules also positively correlates with the age of the households.

Table 1: Correlation between occupancy, energy use and the age of the occupants

Hrs heaters on	**Coefficient**	**Sig.(2-tailed)**
Age of household	-.322*	.022
Members of household with children	.412**	.006
Hrs occupied	**Coefficient**	**Sig.(2-tailed)**
Age of household	.392*	.032
* Correlation is significant at the 0.05 level (2-tailed) **Correlation is significant at the 0.01 level (2-tailed)		

The survey results also present that although 63% of the respondents are full-time employed, the income level of 58% of the households is below £12K per annum (Figure 3) which highlights fuel poverty as a significant issue and the importance of the energy efficient retrofit. Studies show that in LBN, there is a high rate of fuel poverty at 13.8%, with 13,372 households suffering, which is among the highest rates in the UK (Walker and Ballington, 2015).

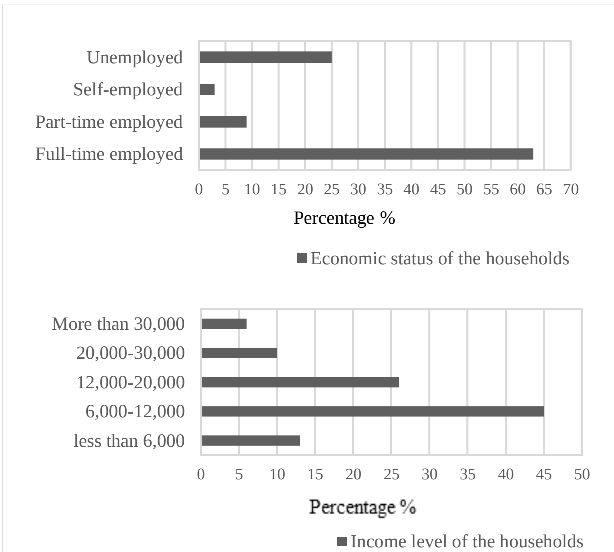

Figure 3: The economic status and income levels of the households of the surveyed properties

As mentioned previously the tower block experiences the significant damp, mould and condensation issues and at least around 40% of the respondents stated that they usually experience the dampness, mould, condensation and draught issues within the flats (Figure 4). It should be noted that 44% of the households admitted that they feel they had to use more heating energy to reduce the condensation and cold and the rest asserted that they open the windows to provide comfortable indoor environment due to illnesses or for the children's comfort. Table 2 shows that as the level of the dampness and condensation issues increases in the surveyed properties, the occupants' tend to pay more gas bills to reduce the issues experienced.

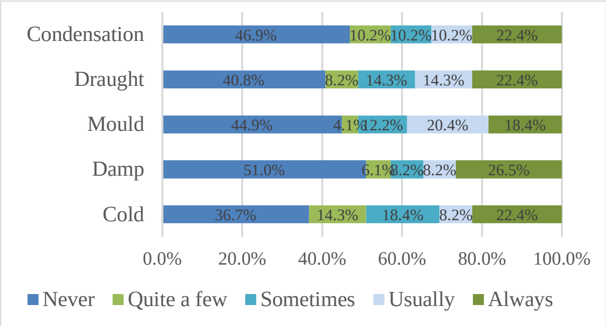

Figure 4: Questionnaire responses in regards to damp, mould, condensation, draught and cold issues experienced in the surveyed properties

Table 2: Correlation between damp, moulds, condensation issues with the Energy bills

Experiencing Damp	Coefficient	Sig.(2-tailed)
Gas bills	.626**	.005
Experiencing Condensation	**Coefficient**	**Sig.(2-tailed)**
Gas bills	.379*	.033
* Correlation is significant at the 0.05 level (2-tailed) **Correlation is significant at the 0.01 level (2-tailed)		

Furthermore, half of the respondents admitted that they never use extractor fan while taking the shower mainly there is no extractor fan within the properties or they are out of order. However, a few of the occupants never use the extractor fan due to the noise level. The result shows that using the extractor fan have a significant impact on reducing the damp and condensation and the occupants energy use behaviour have an effect on the levels of the issues experienced. From the in-depth analysis of the survey results, it was found that occupancy data including energy use behaviour, socio-demographic backgrounds as well as physical issues of the properties including dampness and mould contribute to the total building energy use as well as energy consumption and occupancy schedules.

Building performance modelling

In order to evaluate the building performance in the winter season and validate the monitored data against the predicted results, building simulation modelling and analysis has been performed using DesignBuilder software (DB). DB is an advanced building environmental simulation tool that uses EnergyPlus dynamic simulation engine for the simulation analysis (DesignBuilder, 2018).

In order to calibrate the building performance, as well as the building materials and components that were adopted in the simulation model, the measured indoor environmental data in the monitored flats (flats A and B) were scrutinised in conjunction with DB simulation results. As there has not been detailed specifications available concerning the building materials of the case study, the specifications of the construction materials of typical 1960s council housing tower blocks in the UK were adopted to the case study to develop a representative simulation model. The typical U-values for this type of buildings in the 1950s/1960s are 0.78 W/ m^2K for external walls, 1.82 W/ m^2K for internal floors, 0.28 W/m^2K for roof, 2.67 W/m^2K for glazing, 2.82 W/m^2K for internal doors and 2.93 W/m^2K for internal partitions (Malpass and Walmsley, 2005, Harrison and De Vekey, 1998, Colquhoun, 2008).

To increase the accuracy of the predicted building performance, a modified weather data set in EnergyPlus weather format (epw) was incorporated to DB model using Met Office outdoor environmental data of the nearest weather station to the building location along with the actual occupancy and energy use patterns of the representative flats including lighting, heating and ventilation. The airtightness of the case study flats were also defined "poor" as there were many complaint regarding damp and draught inside the properties during the winter months. The occupants of these properties also reported about the significant increase of the heating energy consumption since these issues were noticed. It should be noted that natural gas-fired boilers facilitate heating in the properties by wall mounted radiators, which were also defined in the simulation model.

Figures 5 illustrates the monitored indoor air temperature against the DB predicted results during the coldest week of the monitored period in the winter season.

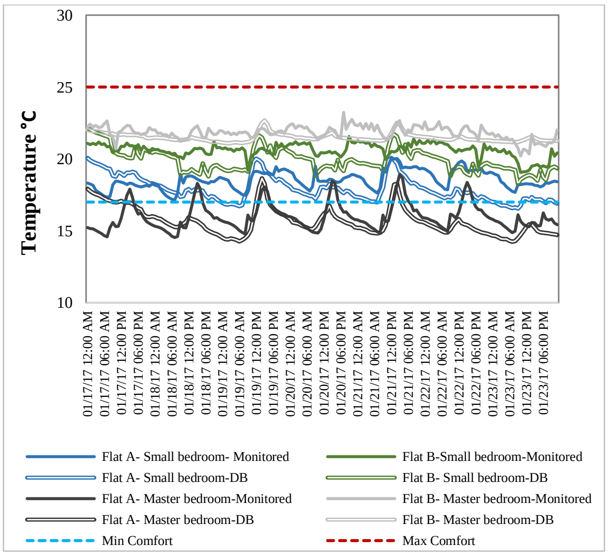

Figure 5. Indoor monitored air temperature against DB predicted results in the representative flats

It can be seen that the percentage variation between the monitored and the predicted indoor air temperature is between 5% and 15%, which has been asserted as an acceptable variation (FEMP, 2015) and demonstrated that the simulation model matched the real building.

The impact of occupancy and energy use patterns on the predicting energy use

The results from the survey questionnaire combined with the outcomes from the water ingress survey conducted by the council informed the selection of two exploratory sample flats (flats A and B), which are characterised by having the (lowest and highest) dominant occupancy profiles, both had relatively high energy bills, and experienced similar issues with their indoor environment. Both flat occupants also felt they tended to use more heating energy to reduce discomfort caused by damp, mould and condensation. Flat A is occupied by a retired occupant (representative for low occupancy pattern) and Flat B is occupied by a young family of five including three children (representative for high occupancy profile). The socio-demographic status of the occupants indicate that 31% of the properties are occupied by a single occupant (low occupancy), while 31% of the properties are occupied by four to seven people (moderate to high occupancy).

The occupancy and energy use patterns of the exploratory sample flats were incorporated into the simulation model separately as two dominant scenarios to predict the energy use of the tower block. The building performance using the representative occupancy and energy use profiles was also compared against the building performance using CIBSE technical memorandum 59 (TM59) occupancy patterns and Standard Assessment Procedure (SAP 2012) energy use patterns. CIBSE TM 59 is a newly developed guideline for the assessment of overheating risk in new and refurbished dwellings (CIBSE, 2017) while SAP 2012 is the UK government's procedure developed for the energy rating of dwellings (DECC, 2014). As the subsequent phase of this study is to determine an energy-efficient retrofit strategy, overheating risk will form one of the main concerns of the study.

Table 3 presents the schedules of heating energy use as well as occupancy patterns using three different scenarios (dominant patterns vs. Standardised patterns) in the main rooms of the properties that were applied to DB simulation tool. As presented in Table 3, Flat A occupant, an elderly person, keeps the heating off in both bedrooms whilst keeping the heating on from 8:00 am until 10:00 pm in all other zones of the flat with the thermostat set at 19 °C. The occupant also never opens any windows during the winter season for ventilation purposes. On the other hand, Fat B, occupied by a family of two adults and three children, always turn the heating on from 8:00 pm until 7:00 am in both bedrooms with the thermostat temperature at 25°C, whilst heating is turned off in all other zones in the flat during a typical winter day. However, the recommended heating schedule in SAP is for 9 hours during the weekday.

Figure 6 shows the predicted the heating energy loads of the tower block in a cold winter month of January using the three different scenarios of the occupancy and the energy use patterns including the dominants scenarios as well as standardised patterns.

Table 3: Dominant low and high heating and occupancy patterns (Flat A and Flat B) of the case study and the Benchmark Patterns (SAP and TM)

Scenarios		Flat A	Flat B	SAP and TM
Bedroom	Heating	-Off	-6:00pm to 8:00am. -On for extra hours from 12pm or 1pm for 3 h in winter.	-Weekdays: Heating on from 7am-9am and 4pm-11pm -Weekends: Heating on in all rooms from 07:00-23:00
	Occupancy	-10pm to 8am	-7pm to 7am	-70% occupancy from 11pm to 8am -Full occupancy from 8am to 11pm
Kitchen	Heating	-8am to 10pm	-Off	-Weekdays: Heating on from 7am-9am and 4pm-11pm -Weekends: Heating on in all rooms from 07:00-23:00
	Occupancy	-1/2h at 8am, at 12:30pm and at 5:00pm	-1h at 6:30am, at 12:30pm and at 6:00pm	-25% occupancy from 9am to 10pm
Living room	Heating	-8am to 10pm	-Off	-Weekdays: Heating on from 7am-9am and 4pm-11pm -Weekends: Heating on in all rooms from 07:00-23:00
	Occupancy	-8am to 10pm	-8am to 10pm	-75% occupancy from 9am to 10pm

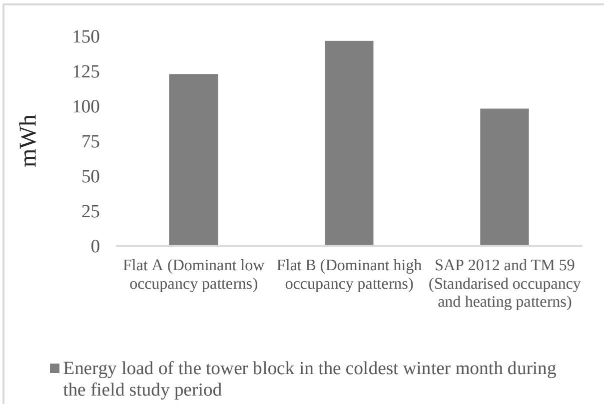

Figure 6: Predicted heating energy use of the tower block in a winter month in Jan 2017 using three scenarios; dominant low and high patterns as well as standardised patterns

It can be seen that the predicted heating energy consumption of the tower block using Flat A scenario (low occupancy patterns) is 20% less than Flat B scenario (high occupancy patterns). In addition, the standardised patterns (TM and SAP), predicted the lowest energy use, which is around 40% less than Flat B' scenario.

The study presents that the occupancy and energy use profiles of the building can be affected by the energy use behaviour of the occupants as well as the buildings physical issues, which in this case are dampness, mould and condensation. These dominant energy and occupancy patterns result in predicting a different heating energy use during the winter season compared against the standardised patterns, which shows the importance of incorporating the exemplary schedules into the building simulation tools to predict feasible building performance.

Conclusion

This study investigates the effect of occupancy and energy use patterns on predicting the building energy performance during the winter season in a residential tower block in London Borough of Newham (LBN). The study used a questionnaire-based survey on the occupants' energy use behaviour, as well as building energy simulation modelling and analysis in order to assess the effect of people's energy use patterns on the buildings energy performance. The focus of this paper is on the winter season as it was found that the building uses significant heating energy in the cold seasons mainly due to the hyghrothermal issues.

The results of the questionnaire survey presented that the occupants' energy use behaviour, and socio-demographic backgrounds have an impact on the energy use of the properties. It was also confirmed that having children in the family results in increasing the heating energy use. In addition, due to the significant damp and condensation issues, the occupants tend to use more heating energy to decrease the effective of dampness. This paper also attempted to compare, quantify and analyse the impact of occupants' energy consumption patterns on building energy performance using dominant scenarios based on real occupancy and energy use patterns obtained from the survey; Flat A and Flat B. The predicted energy use of the building using the dominant patterns were then compared against the outcomes from using the benchmark methodologies (SAP and TM). The results from the simulation showed that the energy consumption of the case study in the winter season is almost 40% less when using the benchmark patterns in comparison to when using the dominant high occupancy and energy use profile (Flat B), while it is 20% less when using the low occupancy profile (Flat A).

The study shows that it is not always possible to rely on standard methodologies for predicting a feasible building performance for a case study with hydrothermal issues as the occupants' energy use patterns might be different. In addition, the occupants' age and economic levels also have an impact on the energy use. To reduce the gap between the actual and the predicted simulation results, the occupants' energy use behaviour as well as the reliable energy use patterns need to be methodically considered in simulation modelling as a key parameter to ensure the low energy use during the operational stage.

Acknowledgement

The British Council under the Newton Institutional Links project fund (Grant number 2015EGY01) has funded this research project. The authors acknowledge the support of Newham Council in London for facilitating the survey and monitoring of the case study.

References

ADEME and Agency, (2015). *Energy Efficiency Trends and Policies in the Household and Tertiary Sectors- An Analysis Based on the ODYSSEE and MURE Databases*. French Environment and Energy Management Agency.

Aerts, D. *et al.* (2014). 'A method for the identification and modelling of realistic domestic occupancy sequences for building energy demand simulation and peer comparision', *Building and Environment*, 75, pp. 67–78.

Ahmed, K. *et al.* (2017). 'Occupancy schedules for energy simulation in new prEN16798-1 and ISO/FDIS 17772-1 standard', *Sustainable Cities and Societies*, 35, pp. 134–144.

BEIS (2017). *Energy Consumption in the UK*. Department for Business, Energy & Industrial Strategies.

Chang, W. and Hong, T. (2013). 'Statistical analysis and modeling of occupancy patterns in open-plan offices using measured lighting-switch data', *Building Simulation*, 6(1), pp. 23–32.

CIBSE (2017). TM59: Design methodology for the assessment of overheating risk in homes. London: The Chartered Institution of Building Services Engineers

Colquhoun, I. (2008). *RIBA Book of British Housing: 1900 to the Present Day,* Oxford, Architectural Press.

DECC 2014. SAP 2012- The Government's Standard Assessment Procedure for Energy Rating of Dwellings. Watford: BRE.

DesignBuilder, (2018). 'DesignBuilder Simulation Software'[Online].Available: https://www.designbuilder.co.uk/software/product-overview. [Accessed: 17-May-2018]

EBC, (2016). *Definition and Simulation of Occupant Behavior in Buildings- ANNEX 66*. Energy in Buildings and Communities Programme.

FEMP, (2015). M&V Guidelines: Measurement and Verification for Performance-Based Contracts Version 4.0.

Harrison, H. W. & De Vekey, R. C. (1998). *BRE Building Elements: Walls, Windows & Doors*, London, BRE Press.

Heidarinejad, M. *et al.* (2017). 'Actual building energy use patterns and their implications for predictive modeling', *Energy Conversion and Management*, 144, pp. 164–180. doi: 10.1016/j.enconman.2017.04.003.

Newham Council, (2016) *Water Penetration Survey*. London.

Newham Council, (2007) *Typical Floors Plans of the Tower Block in LNB*, London Borough of Newham: London.

Malpass, P. & Walmsley, J. (2005). *100 Years of Council Housing in Bristol,* Bristol, UK, Faculty of the Built Environment, University of West England.

Medhurst, J., Turnham, C. and Partners, J. R. and (2016). *Damp Survey for London Borough of Newham*. London.

Rouleau, J., Gosselin, L. and Blanchet, P. (2018). 'Understanding energy consumption in high-performance social housing buildings: A case study from Canada', *Energy*, 145, pp. 677–690. doi: 10.1016/j.energy.2017.12.107.

Song, K. *et al.* (2017). 'Predicting hourly energy consumption in buildings using occupancy-related characteristics of end-user groups', *Energy and Buildings*, 156, pp. 121–133.

Stazi, F., Naspi, F. and D'Orazio, M. (2017). 'A literature review on driving factors and contextual events influencing occupants' behaviour in buildings', *Building and Environment*, 118, pp. 40–66.

University of Southampton, (2016). *Occupancy Patterns Scoping Review Project*. Southampton.

Walker, S. & Ballington, R. (2015). London Borough of Newham Annual Fuel Poverty Report 2013-14. London.

Yan, D. *et al.* (2017). 'IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings', *Energy and Buildings*, 156, pp. 258–270.

Zahiri, S. and Elsharkawy, H. (2017). 'Building Performance Evaluation for the Retrofit of Council Housing in the UK: A case study of a tower block in London', *PLEA 2017, Passive Low Energy Architecture- Designto Thrive*. Edinburgh: NCEUB 2017, pp. 941–947.