

PASSIVHAUS POST OCCUPANCY EVALUATION AND PROPOSED BIM-BASED INTELLIGENT MODEL

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Abstract

Passivhaus has been gradually adopted worldwide as the main voluntary building performance standard. While numerous governmental policies and environmental initiatives have promoted the use of low-carbon housing in the UK, the value of Passivhaus has not been fully realised. This paper focuses on UK Passivhaus homes through the perceptions of end-users living in large-scale developments. Case studies are used to obtain feedback on the buildings' performance in the use phase via questionnaire. All surveyed Passivhaus properties were perceived to be very comfortable during the winter, autumn and spring seasons; however, residents were less satisfied with thermal comfort in the summer. This suggests that the standard needs to continuously evolve to address occupant needs. Digital tools can play a role to achieve this. The study concludes a BIM-based process for post occupancy evaluation to overcome heating and thermal discomfort issues.

Introduction

Being responsible for 19% of total greenhouse gas emissions and over 25% of total energy consumption in the UK, decarbonisation of the building sector, especially housing, is crucial in meeting UK's overarching climate targets (UK Housing, 2019). To achieve this, the UK government over past 10 years announced a transition towards zero-carbon buildings and launched the Code for Sustainable Homes policy to assess, certify and promote zero-carbon sustainable design and construction in new buildings (McLeod et al., 2012). However, with the subsequent 'watering-down' of the zero-carbon legislation and eventual withdrawal of the Code for Sustainable Homes in 2015, the UK construction industry has started to debate the validity of the zero-carbon concept as a realistic target (Lynch, 2014). There has been an ongoing debate amongst Architecture Engineering and Construction (AEC) professionals as to how best to address significant carbon reductions, rather than zero-carbon in construction, and whether to deal with materials, fabric, or occupant behaviour. Unlike the net zero-carbon housing policy which primarily focuses on carbon emissions and offsetting by using intensive renewable energy, the Passivhaus standard concentrates on user comfort and conserving energy through a thermally-efficient fabric, passive solar design, airtightness, thermal-bridge-free construction and use of Mechanical Ventilation and Heat Recovery (MVHR).

Several studies have indicated that the Passivhaus standard performs considerably better compared to both conventional and low-carbon housing in the UK (8, 9, 10) and its delivery and adoption in the industry have been limited to approximately 124 units a year, which is 0.07% of

170,000 new-build homes annually constructed in the UK (Ministry of Housing, 2020). Factors suggest that slow Passivhaus standard uptake could be a result of the general private housing sector's reluctance to innovate and adopt energy-efficient home standards (Goodchild and Walshaw, 2011). Concerns with the Passivhaus standard such as its complexity and higher build costs as well as issues regarding excessive insulation, overheating, MVHR and necessary lifestyle changes as a hindrance to its delivery at scale are also factors affecting the adoption (Forde et al., 2020), (Zhao and Carter, 2020), (Pitts, 2017). Hence while there is a public aptitude for low-carbon housing, the construction sector has been not responsive to such needs.

This paper aims to investigate the contemporary drivers of and barriers to delivering the Passivhaus standard in the UK from the user perspective, covering both primary and secondary data. This is achieved through (a) analysing three distinct large-scale residential Passivhaus developments and comparing their occupant experiences, and (b) examining Passivhaus occupants' behavioural patterns and identifying habits/factors that influenced perceived thermal comfort through targeted post occupancy evaluations (POE). The study also proposes a BIM-based intelligent post occupancy evaluation model as a future direction.

Research method

The study adopts quantitative research by conducting a questionnaire through case studies. A total of 174 properties across three different passive house developments are included. Quantitative research in the form of POE was employed as it allowed to gathering of firm, factual data on how the completed Passivhaus buildings were being operated and provided a 'snapshot' of its users' experience and satisfaction at this particular time (Fellows and Liu, 2021). This is vital as the research is trying to identify trends and themes from a variety of cross-comparable accounts (Lucas and Lucas, 2016). POEs have become the preferred industry method to monitor in-use building performance and assess energy performance and air quality as well as collect feedback on thermal comfort, space use, and overall user satisfaction (Meir et al., 2009). The questionnaire was prepared following guidelines from the Post Occupancy Evaluation Toolkit (HEFCE, 2006) as well as specific POE examples (Mlecnik, 2013a). The POE was divided into seven sections including (1) background, (2) occupancy, building type, and use, (3) thermal comfort, (4) energy use, (5) building services and ventilation, (6) air quality and behavioural patterns, and (7) overall impressions. The questionnaire was comprised of 38 questions in total. Most questions were either a checkbox or multiple-choice; however, a 5-point Likert rating scale was also utilized in questions relating to user satisfaction, per-

ceived thermal comfort, air quality, and energy-savings. POEs were collected between September and December 2019 through door-to-door canvassing, postal surveys as well as invited online questionnaires. A total number of 49 POEs were cumulatively collected across the three case studies. Within the scope of this study due to the space limitation, the focus will be on the thermal comfort and behavioural change, living standard improvement and overall satisfaction.

Collected POE questionnaires were then imported into statistical software, Statistical Package for the Social Sciences (SPSS), for further quantitative analysis. Each POE question and the collected answer was correspondingly coded into either a nominal, ordinal or scale variables and analysed to find frequencies, associations and correlations between the answers. Firstly, the analysis was run on nominal demographic variables such as age, gender, tenure, house type, etc. to identify reoccurring occupant and household types, which were then compared to determine if they presented differences regarding comfort, energy savings and satisfaction. The analysis was then conducted on occupants' motivations to live in a Passivhaus property. Lastly, collected data were examined to determine perceived behavioural change, living standard improvement and overall satisfaction with the properties across the case studies. As the majority of collected data was nominal, not normally distributed, and the sample size was fairly limited, non-parametric statistical methods had to be used (George and Mallery, 2019). Therefore, depending on the level of measurement, the collected data were analysed using either a crosstabulation test to determine the association; Mann-Whitney U-test to compare differences between independent groups; or Spearman rank-order correlation to measure the relationship between different variables (George and Mallery, 2019). Particular attention was given to ordinal Likert scale questions asking occupants to rate their satisfaction with a particular aspect of their Passivhaus dwellings such as thermal comfort.

Case studies

Three case studies of the main large-scale residential Passivhaus developments in the UK were conducted to analyse their inception, delivery, and real-life occupancy. The case study methodology was selected for the research as it enabled practical analysis of a broad phenomenon such as Passivhaus standard integration in the UK, which otherwise would have been difficult to examine (Feagin et al., 2016). Investigations by Robert K. Yin highlighted case studies can 'shed empirical light on some theoretical concepts or principles' (Yin, 2009). Just as a laboratory experiment, instead of trying to extrapolate empirical probabilities (statistical generalisation), it allows us to investigate, expand and generalise existing theories (analytical generalisation), e.g., living in a Passivhaus affects occupants' behaviour and perceived comfort (Yin, 2009).

Passivhaus case studies were chosen based on their scale, time of construction, location as well as type of tenure,

thus aiming to acquire currently lacking typological data identified by the literature review. The Forgebank project in Lancaster was chosen as a case study because it is currently the only certified Passivhaus cohousing project in the UK, hence providing a unique insight into energy use and behavioural patterns in a highly interactive and social co-housing environment. Racecourse Estate project was chosen because of its specialised design for occupants with mobility needs as well as for having the best co-heating test results among all monitored Passivhaus dwellings in the UK. Finally, the Goldsmith Street project in Norwich was chosen because it is the biggest Passivhaus development in the UK to date as well as the only Passivhaus and social-housing project ever to win the Royal Institute Building Architects (RIBA) Stirling Prize 2019 for excellence in architecture. Besides, all three case studies were chosen so they would differ from each other in terms of their location, size, completion date, and tenure, therefore allowing us to examine the Passivhaus standard under varying conditions.

Case study 1: Forgebank Co-housing

Forgebank Co-housing is a 41-dwelling affordable community housing project in Halton, Lancaster built in 2013. The project comprises a range of house types ranging from flats to two and three-bedroom terraces. 35 of these dwellings are within the co-housing scheme with shared community facilities. All dwellings in the project were designed to Passivhaus, Lifetime Homes and Code for Sustainable Homes level 6 standards (Passivhaus Trust, 2020). At the time of its construction, Forgebank was the second-largest Passivhaus development in the UK and it still is the largest and only Passivhaus cohousing project in the UK. The development went beyond the fabric performance requirements of the Passivhaus standard. It utilised a biomass district heating system, solar thermal network as well a community micro-grid powered by the hydro-electric scheme and photovoltaic panel array mounted on most dwellings' roofs (Lancaster Cohousing, 2020). A review of the building performance evaluation (BPE) revealed that energy-performance aspirations and the Passivhaus methodology were adopted early in the project and Passive House Planning Package (PHPP) software was used to model and test different design options while an airtightness champion was appointed by the contractor to overlook air-barrier installation and air pressure tests (Innovate UK, 2016). Overall, the dwellings were built to a very high standard and performed exceptionally well in co-heating tests, thus practically eliminating the energy performance gap (Lancaster Cohousing Project, 2013).

Case study 2: Racecourse Estate

Racecourse Estate is a 28-bungalow housing development for elderly residents with mobility needs built in 2011 as part of a wider Racecourse Estate regeneration masterplan aiming to replace old housing stock with 4,000 sustainable new dwellings - comprised of 25 terraced (Passivhaus cer-

tified and CfSH level 4), and 3 detached bungalows (CfSH level 5) designed specifically for mobility-impaired tenants (Technology Strategy Board, 2014). At the time of its completion in 2011, Racecourse Estate was the largest Passivhaus development in the UK and currently is still the largest Passivhaus development in the North East of England (Passivhaus Trust, 2013). Each house was designed to have an open-plan living and kitchen area, two bedrooms and a mezzanine floor which functioned both as plant roof and loft space, with a total floor area of 66 m². External walls and roofs were constructed using prefabricated timber cassettes filled with high levels of insulation, while the ground floor was built using a traditional reinforced concrete slab with 300mm insulation and a screed above, with several good areas of practice during construction including careful detailing, fixing damaged areas and use of appropriate gaskets and putty to seal any gaps in service penetrations (Technology Strategy Board, 2014). Moreover, very close collaboration between the project architect and the contractor was observed throughout the project with numerous training events and workshops to ensure on-site construction met raised airtightness and quality targets.

Case study 3: Goldsmith Street

Goldsmith Street is a large social housing scheme built in Norwich city as part of a city council's wider corporate plan to address increasing social housing needs and tackle fuel poverty (Priest, 2019). The development is comprised of 105 units: 45 two-bed terraces and 60 one-bed flats, and arranged in seven terrace blocks laid out east-to-west emulating the Victorian street layout of the adjacent 'Golden Triangle' district (Waite, 2019). In 2019 the Goldsmith Street development was nominated and won the RIBA's Stirling Prize for excellence in architecture becoming both the first Passivhaus and social housing project ever to win such an accolade (Passivhaus Trust, 2019). Moreover, with 105 housing units, Goldsmith Street became the largest Passivhaus scheme in the UK to date (Figure 1).



Figure 1: Goldsmith Passivhaus Development, image by <http://www.mikhailriches.com/>

Unlike many projects of such scale, the project was delivered through a traditional procurement route which in hindsight allowed the architects to have better con-

trol of the build quality, value engineering and retaining the project's initial design aspirations (Waite, 2019). Throughout the project, the design of the buildings took priority: special attention and care were taken to ensure the Passivhaus standard was working for the design rather than the design becoming subservient to make the Passivhaus work (Greengauge, 2020).

Results of Post Occupancy Evaluations

Post-occupancy evaluations were conducted in three different Passivhaus developments varying in their scale, location, typology and ownership (Table 1).

Table 1: House types identified across the case studies

Case	House Type	Construction Type
Forgebank, Halton [Co-housing]	Terrace, End-of-terrace, Flat	Masonry cavity
Racecourse Estate, Houghton-le-Spring [Affordable housing]	Terrace, End-of-terrace, Semi-detached	Timber frame
Goldsmith Street, Norwich [Social housing]	Terrace, End-of-terrace, Flat	Timber frame

Thermal comfort and heating control behaviour

Collected POE data indicated that all surveyed Passivhaus properties were perceived to be very comfortable during the winter, autumn and spring seasons; however, residents were less satisfied with thermal comfort in the summer months. Overall 22% identified they were either less or not pleased with indoor temperatures during the summer season, referring to overheating as the main issue. Concerning heating, SPSS analysis revealed there were some notable differences between the case studies in terms of heating control behaviour and devices used to control indoor temperature.

A comparison of winter heating patterns (Figure 2) highlighted that Goldsmith Street had the most habitual residents. They were likely to have the heating on at a predetermined time of day, i.e. mornings and evenings. In contrast, Forgebank occupants could be considered the most 'reactive' - typically heating their properties only when felt needed. Racecourse Estate residents, on the other hand, were found to be the most energy-conserving, over half of which indicated never needing to have the heating on in their properties.

In terms of heating control and ventilation devices (Fig-

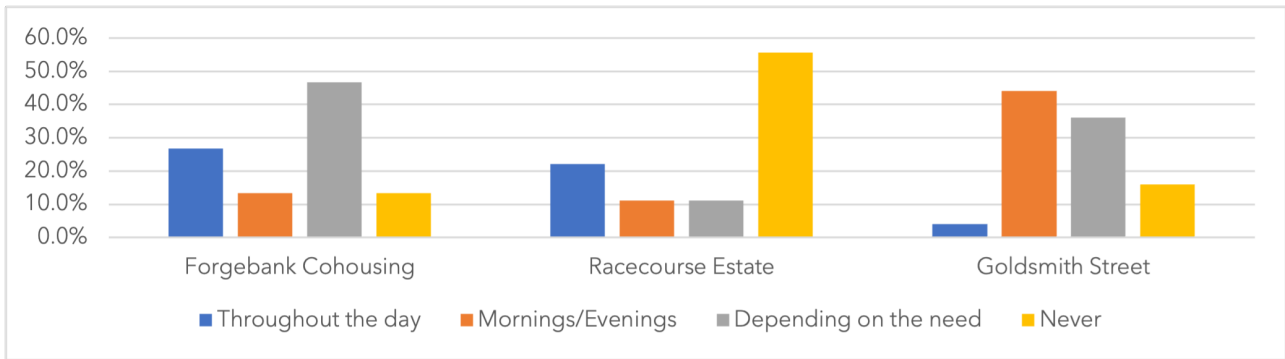


Figure 2: Comparison of winter heating patterns by users across the different case studies

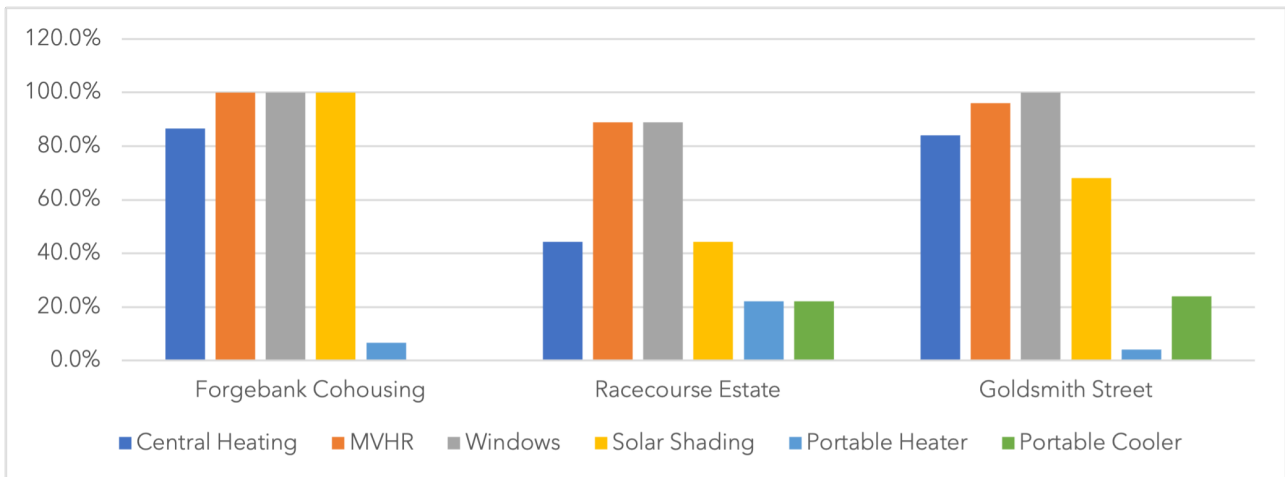


Figure 3: Comparison of winter heating patterns by users across the different case studies

ure 3), collected data indicated that Forgebank and Goldsmith St. residents were still heavily reliant on a conventional central heating system (used by >80% of respondents), in contrast to Racecourse Estate where only 44.4% of end-users reported needing the central heating. That said, Racecourse Estate inhabitants were also found to be the most likely to need a portable cooler to prevent summer overheating, as opposed to Forgebank and Goldsmith St. residents which indicated a much lower need for cooling. All case studies indicated a high use of MVHR and operable windows. Yet, notably, fewer Racecourse residents reported using solar shading, which might explain the summer overheating and need for additional cooling.

Living preferences, lifestyle and overall satisfaction

The last section of the POE research focused on occupants' general perceptions, overall satisfaction and changes to daily lifestyle. Firstly, research participants were asked to identify three main reasons why they chose to live in their Passivhaus property. Radar charts (Figure 4) showed that 'sustainability' was ranked to be the top priority for choosing to live in a Passivhaus across all three case studies (71%). Other top reasons were found to be 'house type' (47%) and 'house price' (43%) while 'community' was ranked as a top priority in the Forgebank development. Research participants were then asked if living in a Pas-

sivhaus has caused a change towards a more sustainable way of life. Collected data revealed that the majority of occupants (41 out of 49) believed living in a Passivhaus has influenced them to adopt a more sustainable lifestyle with 33% of participants reporting a significant change, 49% reporting moderate change and 18% reporting a slight but noticeable change. In terms of overall satisfaction with Passivhaus buildings, collected POE data highlighted that surveyed residents were exceptionally pleased with their homes across all three case studies. Approximately 94% of all participants said they were satisfied or very satisfied with their homes, 6% were neither satisfied nor dissatisfied, and there were no occupants who were dissatisfied with their homes. Furthermore, 65% of residents reported that living in a Passivhaus has significantly improved their living standard, 33% identified a moderate improvement, and 2% found that living in a Passivhaus has not affected their standard of living. In retrospect, 98% of surveyed end-users reported they would recommend it to their friends and family as well as choose to live in a Passivhaus home again if given the opportunity.

Summary of the results

Post-occupancy evaluation data and subsequent SPSS analysis revealed there were significant differences between the case studies in terms of their occupant demo-



Figure 4: Residents' preferences for Passivhaus elements from the three different case studies

graphics, household types, occupancy and heating patterns as well as heating and cooling strategies. Nonetheless, the SPSS analysis also indicated many commonalities and re-occurring patterns between the case studies regarding thermal comfort and overall satisfaction.

Examined POE data revealed that Passivhaus dwellings across all three case studies were found to be exceptionally comfortable during the winter, autumn and spring seasons. However, all three case studies were also found to have consistently lower thermal satisfaction in the summer months due to reported overheating. Out of the case studies, Racecourse Estate was found to have the lowest summer comfort satisfaction with a mean value of ($\mu = 3.33$). Such results confirm previous study findings on the Racecourse Estate, where substantial overheating was recorded (Siddall et al., 2014), (Fletcher et al., 2017). In terms of overall satisfaction, collected POEs indicated that very high user satisfaction was reported across all three case studies despite significant differences between the Pas-

sivhaus properties. The vast majority of residents identified being either satisfied or very satisfied with Passivhaus thermal comfort, energy savings, building services, air quality as well as the overall effect it had on their standard of living.

Such high levels of reported occupant satisfaction confirm previous Passivhaus research findings from both Continental Europe (Cutland, 2012), (Mlecnik, 2013b) as well as the UK (Siddall et al., 2014) where Passivhaus properties were found to be exceptionally comfortable and energy-efficient.

Proposed POE model

Questionnaire results reveal that a more structured POE process is needed to monitor the Passivhaus performance during the occupancy. POE is not structured and not linked to the characteristics of BIM in the design phase. Materials used and the impact of building materials such as conductivity and location etc. are not evaluated during the use

BIM-based Intelligent Post Occupancy Evaluation

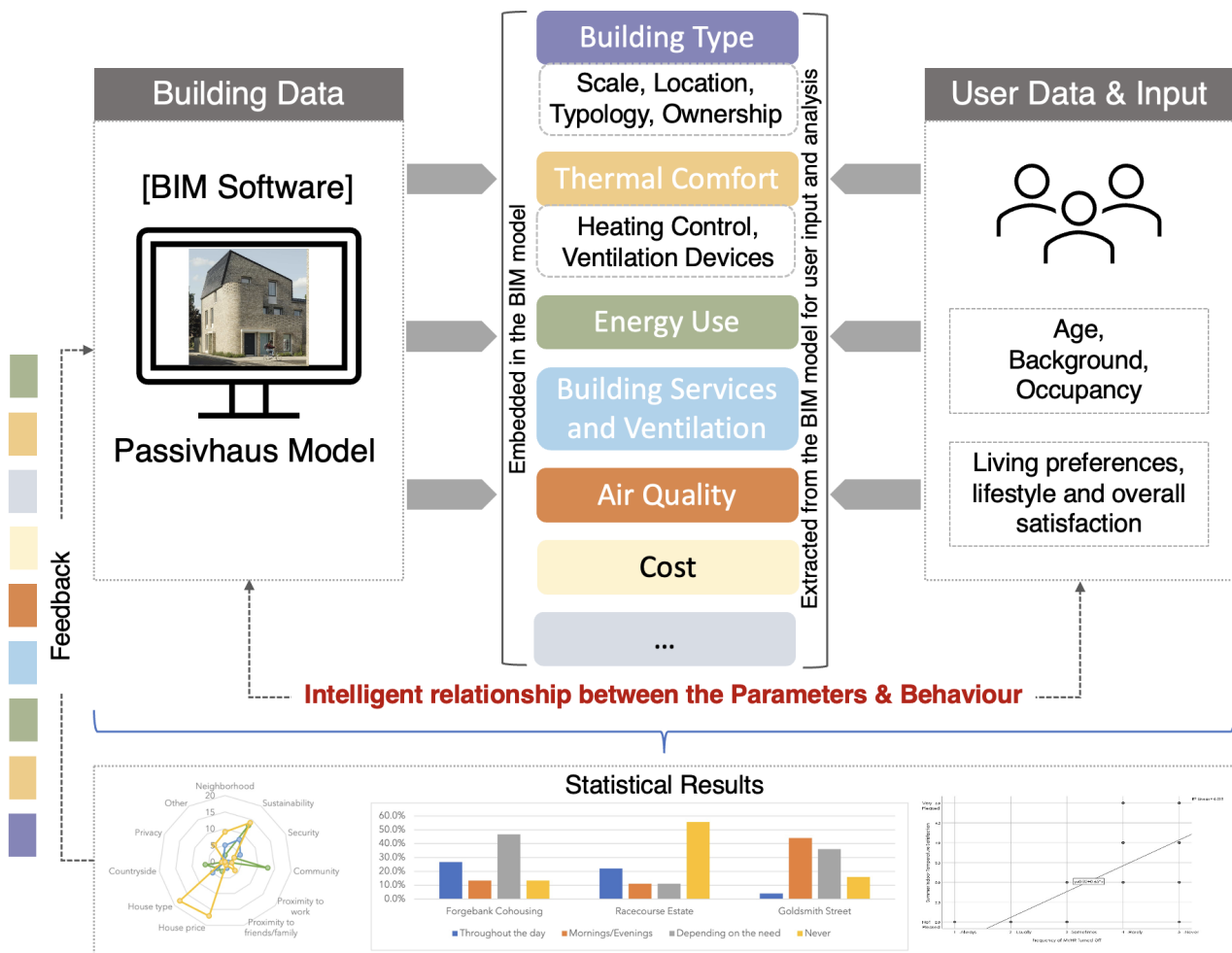


Figure 5: BIM-based intelligent post occupancy evaluation model

phase of the building life cycle.

BIM and other intelligent technologies can help adjust the optimum indoor comfort and energy use as well as identify the related problems based on the actual data for the occupants. Passive houses are very specific and have special features and details, the data should be reflected in the BIM models.

Within the scope of this study, a conceptual attempt was made due to the lack of passive house and BIM data. Enrichment of the BIM model and passive house is possible using the parameters such as building type, thermal comfort, energy use and cost etc. Based on the available data within the BIM model, for example, scale and location can be mapped easily while air quality and energy use cannot be easily integrated until data is available after several years of building occupation. As a baseline, the proposed model is expected to be used enriched for future research and provide solid results. Figure 5 presents a BIM-based intelligent post occupancy evaluation model.

Towards a more digitalised built environment, to facilitate

the adoption of Passivehaus, and improvement of design decisions and consequently user satisfaction, automated and smart solutions should be utilised. A prototype sensor visualisation platform can be designed to connect in-use performance data to BIM context data to provide actionable advice for landlords and tenants for minimising repair and maintenance activities. This is mainly because assets do not perform as well as they should when built by comparison to the design phase (Lewry, 2015). Such variations have increased the appetite for carrying out post occupancy evaluation as mentioned in this paper for normally built domestic and commercial assets, however, this is not necessarily the case in the passive house due to the strict air tightness regulations and conditions. This study has revealed that there are still issues associated with important aspects such as the 6 factors mentioned in the model, which are not always integrated with a user-driven feedback process for better building operations for passive buildings. Application programme interfaces (API) could be linked into the system to provide further insight into the condi-

tions that affect housing assets. The measurement of light levels requires further investigation to acknowledge tenant behaviour patterns such as only requiring light at certain times for certain activities (Rogage et al., 2020). In this case, APIs could record simple temperatures, and since the data could be used over time within passive house properties to influence thermal comfort levels, this can prevent issues such as overheating. The data centres could be connected to thermal satisfaction interfaces which could be modified every day depending on the rating given by the occupant on a sliding scale. Thus, over time an optimised model can be developed by feeding this data back into the BIM model specifically designed for asset management of passive houses. Furthermore, the development of artificial intelligence (AI) is a huge potential for programming such processes to take into account occupancy feedback within the building to reduce consumption even more.

Conclusion

This study aimed to analyse the Passivhaus standard in the UK in its present condition through current occupant experiences and discuss the future direction via the proposed POE model. Forty-nine post-occupancy evaluations conducted in three separate case studies across the UK revealed that occupants were generally very pleased with their Passivhaus dwellings. Residents reported high levels of satisfaction with both internal thermal comfort and perceived impact on health. In general, research results were consistent with previous literature findings and the hypothesis that the Passivhaus methodology can deliver highly comfortable homes and substantial energy and carbon savings regardless of the building's location, occupancy or construction. Participants believed that the Passivhaus standard had the potential to evolve to form a foundation for a more robust sustainable housing policy and improvement in understanding occupant behaviour currently lacking in the industry. The findings also highlight there has been a significant lack of longitudinal research and POE of Passivhaus properties over a long period to investigate the longevity of its thermal properties as well as the involvement of end-user experience. Therefore, up-to-date research investigating the current construction industry's perceptions of the standard as well as revisiting occupant experience in large-scale Passivhaus properties to gain deeper understanding is needed over the long term as we move towards ever more stringent low-carbon targets, through more automated and digital solutions.

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