Assessing the impact of a differentiated retrofit approach in UK domestic buildings

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Abstract. Conventionally, publicly accessible retrofit recommendations use calculations based on standardised occupant behaviour. However, studies have shown that occupant behaviour can have a significant impact on energy consumption and subsequent retrofit savings. This paper assesses the impact of a differentiated retrofit approach using household archetypes grouped according to similar behavioural patterns, dwelling and household characteristics. The results showed that distinguishing between different household groups can significantly improve overall retrofit effectiveness. The ambition is to enable better home retrofits for a sustainable housing stock, while meeting the UK Government’s goal of carbon emissions reduction.

1. Introduction
Building energy retrofit shows promising potential for CO₂ emissions reduction, energy conservation and better building performance [1]. Domestic buildings account for about a third of the UK’s total energy consumption, where the Government has introduced various retrofit policies and programmes to encourage wider uptake of energy efficiency measures [2,3]. However, the introduction of energy efficient technologies has often failed to bring the promised reduction in domestic energy use or CO₂ emissions. The predicted energy savings from retrofit frequently exceed actual savings made due to behavioural factors [4-6]. For example, occupants may change behaviour that can offset the savings from improved energy efficiency by increasing overall consumption [7,8].

Domestic retrofit guidance in the UK has been primarily based on technically oriented energy audits. These audits typically focus on the physical characteristics of the dwellings, using building performance models with standardised behavioural assumptions to measure home energy efficiency [9,10]. Subsequently, the calculations based on these assumptions could undermine the validity of retrofit guidance [11]. Energy performance certificates (EPCs), for example, as a legal requirement for existing dwellings to be sold or rented since 2008, use the Reduced Standard Assessment Procedure (RdSAP) to evaluate home performance as well as to estimate and recommend effective improvements. Designed to assess the building rather than its occupants, RdSAP generates results that are independent of individual household behaviour. This means that the subsequent retrofit recommendations and estimates of the effectiveness of relevant measures are decoupled from any specific occupants. Similarly, as the main agency providing publicly accessible retrofit recommendations, Energy Saving Trust along with its web-tool Home Energy Check have also excluded variations of energy saving potential resulting from different household behaviours. Consequently, retrofitted homes might result in significantly less energy
savings than expected, hindering the process of effectively achieving carbon emission reduction and reducing confidence in investment decision-making.

The significance of occupant behavioural impact in influencing the effectiveness of energy retrofit has been widely recognised [6,12-14]. Better incorporation of behaviours in energy performance prediction can thus improve the reliability of modelling estimation and subsequent retrofit recommendations. However, energy consumption is complex. Employing standard and simplistic behavioural profiles in energy modelling leads to a significant discrepancy between actual usage and prediction [15]. For energy demand reduction, an approach incorporating the complexity of behaviour is needed that captures the key determinants of energy performance to allow better evaluation of energy saving policy programmes and retrofit options. A study using dynamic building simulation showed that occupants’ heating behaviour significantly influenced the energy-saving potential of retrofit measures: active heating users could achieve almost twice as much energy saving as passive heating users [16]. Dodoo et al. [17] found that indoor air temperature influenced performance of energy efficiency measures significantly. Therefore, addressing behavioural variations in retrofits is crucial for achieving the anticipated savings and helping occupants make better-informed decisions.

This paper assesses the impact of a differentiated retrofit approach using household archetypes that incorporate variations of behavioural patterns, household and dwelling characteristics. Current behavioural modelling in building simulations addresses behavioural complexity but excludes occupants’ socio-demographics and household characteristics which are crucial for identifying specific target groups [18,19]. An alternative is to create an archetype for each significant class of household based on statistical analysis, and then examine different ways of tackling energy efficiency according to the characteristics for that archetype. In this context, an archetype is defined as a typical example of households sharing similar behavioural patterns and dwelling physical characteristics. If the archetypes are carefully selected, this procedure enables a tailored evaluation of the household types along with their varied energy consumption patterns and potentially different responses to energy efficiency interventions.

2. Methods
As part of a larger project, this paper focuses on the phase where energy performance modelling was used to assess the effectiveness of retrofits, making comparison between differentiated retrofits and standardised ones based on EPCs. The modelling procedure entailed several sequential steps. First, household archetypes [20] were specified together with a range of retrofit measures to be tested. Then a base case was built for testing retrofit options using the archetypes independent of dwelling change, in order to single out the influence of occupant behaviour [21]. Subsequently, all retrofit measures were simulated one at a time across the archetypes with respective dwelling types in order for their performances to be compared [22]. Finally, the research assessed the impact of a modelling approach incorporating household archetypes (HA) compared with the conventional method used for generating retrofit recommendations in EPCs at urban scale. The energy and cost savings were then compared at both the dwelling and city levels.

The base case was a mid-terraced house, selected from a survey carried out in the previous phase [21] of the project. Five household archetypes along with their percentages, derived also from the survey, were combined with the base case to demonstrate the impact of differentiated retrofits. The city of Cambridge was selected for this demonstration, with the hypothetical scenario being the housing stock comprised of the base case dwellings to simplify the comparison. There were five variations concerning rankings and effectiveness of retrofits based on five household archetypes for the differentiated retrofits of the housing stock, in contrast to the single retrofit solution from an EPC. After determining the estimated cost of each measure, the retrofit options were compared and ranked according to their energy saving per pound spent. Eight retrofit levels were formulated based on the number of retrofit options included. The first level had only one and the most cost-effective measure, while the eighth level included all the measures. The assumption was that households would invest in more cost-effective measures first, while the cost and energy savings were the only factors influencing households’ choices.
of taking up retrofit measures. The Tariff Comparison Rate (TCR) was introduced to calculate the monetary saving potentials resulting from energy demand reduction.

The data for this modelling work came from two major sources: the survey from the previous phase of the project as well as Integrated Environmental Solutions - Virtual Environment (IES-VE) default data and published data such as ASHRAE and CIBSE Guides. A set of the most commonly used energy efficiency measures was identified and incorporated into the building energy modelling. The values of the dwelling parameters before and after the inclusion of these retrofit measures were derived from typical values collected from academic and industrial literature. The inclusion of each measure in the IES-VE building model was achieved by translating the physical aspects of each measure into model inputs. For example, the parameter for external wall insulation was the U-value of the external wall. Furthermore, the cost of each measure was based on current market prices and the most economical options. The values for parameters related to retrofit measures represented the average highest efficiency that can be achieved in practice. In contrast, the values selected for dwellings such as the building envelope and system characteristics showed the real and very inefficient dwelling conditions.

3. Results
This paper illustrated that the performance and ranking of energy efficiency measures varied significantly depending on household archetypes. In other words, the effectiveness of retrofit options for each archetype varied, but their effects tending to be larger in more energy-intensive households. By distinguishing between household groups, each household can work out the most favourable and affordable retrofit strategy. For instance, despite the fact that the insulation of tanks and pipes came out on top, while window insulation ranked bottom across all household archetypes, all the other measures had somewhat different rankings depending on the archetype. Compared with EPCs, choosing retrofit measures tailored to each household archetype can result in over €12 million cost saving annually at the urban level. On the dwelling level, an average household may save over €250 per year on top of the saving estimated from EPCs.

![Comparison of Retrofit Options According to Energy Saving Per Pound](image)

**Figure 1.** Comparison of single retrofit options (excluding tanks and pipes insulation which ranked top for all archetypes) according to energy saving per pound (kWh/m²/year/£) in the case study dwelling.
Figure 2. Extra cost saving potential from eight retrofit levels at the urban level when incorporating household archetypes, benchmarked against Energy Performance Certificates (EPC)

The results showed the ranking of cost-effectiveness of measures varied for each household archetype (Figure 1). For example, smart meters and controls remained the second most cost effective option for active spenders, conscious occupiers and average users, but dropped to third and fifth for conservers and inactive users respectively. Similarly, heating system upgrade was the second best choice for conservers and inactive users, whereas it dropped to third, fourth and sixth for average users, conscious occupiers and active spenders. In spite of the variation in their rankings, all the measures were much more cost effective for households with a higher initial energy use, such as the active spenders and conscious occupiers. In other words, households like active spenders would achieve a much higher return on retrofit investment compared with inactive users.

The HA method was demonstrated to have a significant impact on energy and cost savings from retrofit. At both dwelling and city levels, considerably more savings were achieved from using the HA method compared with that from EPC at most retrofit levels. In particular, the HA method could bring additional savings of over €6.6 to €12 million per year at city scale with all retrofit levels except I and III (Figure 2). While a smaller gap of about €0.8 million was found at retrofit level I, a small negative difference occurred at retrofit level III suggesting more savings came from the EPC method when retrofitting with only the first three measures. Furthermore, on average a dwelling was able to make about an extra €140 to €250 in annual savings at all retrofit levels except I and III when guided by HA compared with EPC. The savings gap was especially prominent at retrofit level II and VI to VIII. Overall, it was shown that using HA to guide the uptake of energy efficiency measures would significantly improve the retrofit saving potential.

4. Discussion and Conclusions

This work demonstrates that using a differentiated retrofit approach can significantly improve energy saving potential compared with the conventional methods that standardise occupant behaviour such as EPCs. Compared with EPC, choosing retrofit measures tailored to each household archetype can considerably improve the energy saving potential, which may result in over €12 million cost saving annually at the urban level, if we assume that the typical dwelling is representative of the potential savings achievable across all dwelling types in Cambridge. The results demonstrated a need to prioritise retrofit measures differently to provide maximum benefit to each archetype in terms of energy saving. This challenges the prevailing methods used for generating retrofit recommendations and programmes that use standardised occupant behaviour, such as Energy Performance Certificates (EPC) and Energy Saving Trust.
Furthermore, targeting higher energy consuming households can bring larger energy savings, especially with building system upgrades and external wall insulation. This is in line with the findings of Wei et al. [16] and Dodoo et al. [17]. However, Marshall et al. [23] suggested the savings from some energy efficiency measures were similar for all three occupancy patterns examined. This contrast could be due to the differences in how the user groups were defined and distinguished in each study, such as by different levels of energy consumption. Thus, knowing how to distinguish between household groups so as to determine that each group has the same optimal retrofit options, is crucial for developing retrofit recommendations. By distinguishing between household groups, each household can work out the most favourable and affordable retrofit strategy.

The differentiated retrofit approach using archetypes has been adopted by a number of researchers on domestic retrofit and energy performance. The majority of them employed building archetypes defined only by dwelling physical characteristics in combination with appropriate proportions to represent the housing stock [24-30]. These building archetypes were categorised based on various variables determined distinctively in each study, subjected to a selection of key variables. For example, variations in space heating were the primary concern for identifying archetypes in the work by Kavgic et al. [27], whereas the TABULA project had fixed three independent variables: location, age and geometry [25]. The primary aim of these studies using archetypes was to develop building energy models for testing retrofit strategies. However, due to a lack of association between these building archetypes and occupant behaviour or household characteristics, large discrepancy may exist as to the actual energy consumption and subsequent retrofit performance estimations related to the archetypes identified.

Meanwhile, there are studies aiming to segment households through distinguishing clusters of behavioural patterns statistically and derive subsequent different energy conservation strategies. For example, Raaij and Verhallen [31] identified five behavioural patterns and found that these behavioural patterns (clusters) corresponded with considerable variations in energy use, and each cluster associated with different socio-demographic and attitudinal characteristics. Similarly, Guerra-Santin [32] identified five behavioural patterns along with certain distinct household and dwelling characteristics connected to each pattern. Previous studies have already revealed different statistical approaches to clustering energy consumers and making household archetypes for targeting energy efficiency improvements. Nevertheless, as every author analysed data collected with a different set of pre-determined parameters and each archetype was derived with an element of subjective interpretation, the resulting clusters and subsequent impacts differ as well.

Overall, retrofit design and policies that use the differentiated retrofit approach can help address the under-realisation of retrofit while maintaining occupant comfort. Such an approach can significantly improve the reliability of retrofit guidance and recommendations. It will not only aid householders in making better-informed decisions on their options for retrofit, but also assist policy-makers in better incentivising a more widespread uptake of retrofit measures.

Acknowledgments
Authors wishing to thank the staffs and members who provided valuable support and assistance at the Martin Centre, Department of Architecture and Wolfson College of Cambridge University. Funding from Cambridge Trust, Wolfson College Cambridge, Lundgren Research Awards, GBCET Chinese Student Awards and Henry Lester Trust Award are gratefully acknowledged.

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