Building Energy Simulation of 19th C Listed Dwellings in the UK: A strategy to propose and assess suitable retrofit interventions

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Abstract. Improving energy performance of Traditional Listed Dwellings (TLDs) in the UK is much needed. However, there are issues to overcome due to their heritage value and to the complexity of their thermo-hygrometric behavior. This on-going research project aims to propose a framework for interventions in TLDs in South East England to improve their energy consumption utilising Dynamic Energy Simulation (DES) of selected case studies in the city of Brighton and Hove, UK. Providing a brief overview of the methodology adopted in this study, the paper describes the approach devised to select the applicable measures for the dwellings investigated. It aims to improve their energy performance while minimizing the risks of unintended consequences on the fabric and occupants, as well as those of loss of heritage value. Therefore, the proposed strategy balances the need for individual solutions, underpinned by consistency in the rationale behind the choice of interventions and materials.

Keywords: Retrofit interventions; Traditional Listed Dwellings; Building envelopes.

1 Introduction

To improve the environmental impact of UK dwellings is unquestionably an urgent task in order to fulfil the target imposed by the recently revised Climate Change Act [1], and to do so for existing building stock and buildings of cultural value is a challenging commitment. This research aims to propose a framework of interventions in Traditional Listed dwellings (TLDs) in the South-East of England, to improve the energy performance, thereby reducing their carbon emissions. To assess the benefits of a range of carefully selected appropriate energy retrofit measures, it utilizes case studies (CSs) and dynamic energy simulation (DES), followed by sensitivity analysis.

A methodological approach to help a systematic choice of retrofit measures from an array of sensible and safe interventions was needed; this is what this paper aims to report on. The outcome of this stage will then be used later, when effectiveness of these measures will be assessed, by applying them, individually and combined, to the models created for simulation. The strategy developed for this initial selection of suitable interventions, aims to minimize the risk of unintended consequences, as well as that of loss of heritage value, by assessing the risks for the thermo-hygrometric balance of the constructions as well as those imposed on the special features which contribute to the heritage value of the buildings. To achieve this aim, the following objectives have been pursued:

1. A review of existing regulation and guidance on retrofit measures for buildings of heritage value and traditional construction.
2. An assessment of relevant features contributing to the heritage value through case study surveys.
3. Verification and confirmation of findings of stages 1 and 2 through expert consultation (in-depth technical interview with conservation officers).

2 Background literature review

18% of all CO_2 emissions in the UK stem from the residential sector [2]; the main source being the use of natural gas for heating [3]. Nevertheless, the UK faces a complex and delicate suite of issues when retrofitting this part of the stock, as it inherits the oldest dwellings in Europe [4], with more than one fifth of the total housing stock having traditional construction [5]. Traditional dwellings (TDs), built before 1919, are characterized by solid, permeable walls, single-glazing and un-insulated roofs and floors [6], therefore, generally poorly performing, but also often of high architectural or historic value, hence listed.

A special approach is necessary when selecting energy retrofit measures for TLDs; one that aims to strike a balance between the need for energy improvements, heritage conservation requirements and thermo-hygrometric balance of their constructions [7,8].

The 'fabric first' approach, supported by BRE [9] and EST [10,11] for housing retrofit in general, is not the one recommended by conservation bodies for TLDs. Firstly, because the "fabric" of TDs needs to be treated with careful consideration. Their thick, solid masonry walls are made of porous, breathable materials. Such constructions allow TDs to buffer both humidity and heat fluctuations [8,12,13]. Unsympathetic measures can irreparably alter their thermo-hygrometric balance, increasing the risks of unintended consequences, due to moisture accumulating, hence condensation and associated problems for the occupants' health and for the fabric [6,12,14]. Hence, measures must firstly be "moisture-safe". Secondly, because when it comes to TLDs, the fabric is where most of their heritage value is, therefore, any intervention must also be extremely cautious. "Sensible" retrofit measures should be aimed at ensuring that the features that contribute to their special character are maintained, hence, their heritage values are sustained and enhanced [5,15].

Therefore, a special approach is advocated for TLDs, unanimously by the conservation bodies and previous research; one that, while aiming to improve the energy performance, takes into account their thermo-hygrometric balance, as well as their heritage value [As indicated in almost all of the general guidance and recommendations e.g. 5,6,12,13,14,15,16,17,27,29,30].

3 Methodology

The study utilizes a mixed method approach on multiple case studies (CSs) of 19th C listed dwellings in Brighton and Hove, UK, selected as representative of the majority of the TLDs population in the South East England (for details about the CSs selection process please see [31]). The cases are all Regency or early Victorian converted flats, belonging to grand terraces of houses (see Figure 1). Their size ranges from 60 to 200 m^2 and they include dwellings on all levels (from lower ground floor/garden flats to top floor flats).

The research is focused on building physical determinants with a potential impact on heating energy consumption, therefore on passive retrofit measures, aimed at the envelope of TLDs only, and does not include behavioural determinants.

The study is articulated around successive stages of (DES). Once the models were created (for details please see [32]), the first simulation was run for the dwellings in status-quo conditions and the data output at this stage was used for calibration with metered data (for more detail on this stage please see [33]).

The calibrated models were then normalized to simulate their standardised status-quo performance. The normalization process devised, included, firstly: heating season, patterns of use and ventilation habits. Finally, the same heating system was applied to all the CSs, upgrading the status-quo with a high-efficiency boiler, as suggested by English Heritage [17,34] and confirmed by previous research [35]. This way, a base-case scenario was generated for each CS, where only the physical determinants play a role in the final heating energy consumption output of the simulations.

The following stage of research, described in this paper, was aimed to select the range of interventions applicable to the CSs. The base-case scenarios are then used, to assess the output of the chosen measures, individually and combined, by comparing the heating energy consumption and associated CO_2 emissions, pre- and post-intervention.

Fig. 1. Brunswick square, one of the earliest regency developments in Brighton.

4 Results and Discussion

4.1 Retrofit measures for TLDs

This stage of the study was aimed at generating the range of sensible and potentially safe retrofit interventions to be tested in the following stage of research. Developing the checklist of interventions, based on what was proposed by Historic England [15] for buildings of heritage value, and adapting it to the specific contextual conditions investigated in this research, three sets of retrofit options were considered applicable to the selected CSs:

- Low risk options: those options that can be easily applied, are the least expensive, not disruptive, totally reversible, minimise the risk of unintended consequences and do not require any planning permission and, generally, Listed Building Consent (LBC);
- Medium risk options: those that imply the use of skilled workmanship and some costs, are more intrusive, need assessment of the risks associated with the occupants and fabric's health and require planning permission, and, most of the times, LBC (although being generally permissible);
- High risk options: those that imply very skilled workmanship, incur higher costs and cause disruption, have potential high risks for the occupants and fabric's health and require planning permission and LBC (often not permitted, however, to be assessed case-by-case).

In order to decide about the individual applicability of the available measures, an heritage significance assessment was first conducted of the selected CSs by means of visual and measured surveys, complemented by a desktop research, together with secondary data collection, to collect and analyse data about the heritage (architectural and historic) value of the buildings and their specific fundamental features in need of protection [34,36]. Indoor temperature and relative humidity data logging, together with thermographic surveys, were then added to the previous methods, to aid understanding the composition of the thermal envelopes and the thermo-hygrometric behaviour of their fabric.

Finally, an expert interview with a highly experienced senior heritage officer (interview with C.O., 12/12/2019), allowed for further refinement of the list of feasible interventions for the individual CSs investigated, with an overview of the actual applicability of the selected solutions in each specific context.

A brief description of the measures available for each area of intervention and their applicability on the CSs selected is as follows:

Whole Dwelling. Draught-proofing, although easily applicable and potentially beneficial to reduce air leakage and heat loss, and therefore heating energy consumption [37,38] could potentially alter the breathability of outer envelops of TDs, for which an adequate ventilation is essential [12,18]. To avoid risks of condensation, a value of 0.5 Ach has been considered desirable, as suggested by guidance and precedent studies [18,30,39,40,41,42,43].

Windows. The current body of regulation and guidance agree in considering historic windows significant and irreplaceable features, that constitute an intrinsic part of the listed building and contribute to the character of its elevation [6,15,28,30]. Therefore, in selecting retrofit measures for TLDs, retention of such elements is of fundamental importance, while aiming at upgrading their energy efficiency as much as possible [6,14].

The low-risk option unanimously encouraged is the use of internal shading devices, such as curtains or blinds [5,15,26,28,30,44]. Shutters can be reinstated without need for LBC, when evidence of their previous existence has been found in the dwelling in object or in other dwellings of the same level in the same listed terrace (interview with

C.O., 12/12/2019). The greatest reductions in heat loss could potentially come from combining these measures, i.e. shutters and heavy curtains [6,45].

Secondary glazing, when the internal detailing of the wall around the original window allows for it, is a straightforward option, and is generally encouraged by conservation bodies [5,6,14,15,16,25,26,28,30]. This intervention is common practice for listed buildings in Brighton and Hove (Interview with C.O., 12/12/2019). The performance achievable by means of secondary glazing can sensibly be increased using low-emissivity glass [13,28,34,45,46,47] and further improved by opting for vacuum slim profile for the secondary glazing [35]. Although not requiring LBC in general, it is considered a medium-risk option, as it implies some level of disruption, higher costs than draught proofing and adding curtains and more skilled workmanship.

While slim double-glazing, is proved to be effective [46] and applicable to listed buildings [48] it is not generally recommended by conservation bodies and is only considered as an extreme measure [15]. Even considering vacuum slim-profile double-glazed units, - which can be as thin as 6.5mm in total -, the insertion of the new units in the original frame, requires very skilled workmanship, often needs a few alterations to frame and glazing bars to accommodate the new glazing and support the increased weight of it, and, overall, has a limited lifespan and does not guarantee the expected outcome [26,28]. Slim-profile double-glazing is extremely unlikely to receive LBC if proposed for an original window in a building of heritage value when the historic frame still retains the original glass [14,15]. The approach of conservation bodies is generally more flexible when the original window is lost and has been replaced with a new, unsympathetic one or the original glass has already been previously replaced [15].

External doors. Historic doors, like windows, are considered important elements that contribute to the character of the elevation and to the heritage value of TLDs [6,15,18,28,30]. Insulating front doors requires LBC and can often be controversial as most of them are original. The decision concerning the actual applicability of such option needs to be taken on a case-by-case basis. Usually, the energy savings achievable with these interventions, are not significant, as front doors are generally made of solid wood and thicker than 60mm, therefore performing better than windows in their status-quo. This measure is often out-weighted by draught-proofing of doorframes [18]. Furthermore, the intervention may not be straightforward, when the door is paned or glazed, which is the case for many Regency front doors.

Ground Floors. When a historic finish is still in place, the range of energy retrofit interventions may be limited and need to be addressed maintaining the moisture equilibrium of the construction and preserving its heritage value [13].

When the floor finishes are not of historic value, adding carpets is a low-risk and easily reversible retrofit option for any type of ground floor construction, as long as the chosen materials are vapour-permeable, to avoid trapping moisture [15]. This solution, however, is considered applicable only when carpets are a practical choice in relation to the use of the space [24,26] (Interview with C.O., 12/12/ 2019). In addition, the use of a vapour-permeable, thin and high-performance insulation board, is a medium-risk option applicable to solid and timber ground floors [15]. The implications of this intervention need to be carefully considered, as it could cause technical problems in adjoining floor levels [15,24] and imply the need to shorten the height of internal doors, as well as to lift original skirting boards, therefore leading to non-permissible changes in the overall proportions of a room (Interview with C.O., 12/12/ 2019).

The use of concrete slab and insulation -generally an impermeable material-, usually with an added layer of damp protection membrane, to replace historic solid ground floors, was a solution often applied during the last few decades to improve the energy performance while protecting against rising damp. However, it has been excluded as an option for TLDs because it has shown to be detrimental for traditional constructions. In fact, it alters the original breathability of the ground floor, inevitably leading to problems of excessive moisture being diverted and absorbed by the external walls, with negative consequences for the occupants, such as poor indoor air quality, and for the fabric, such as timber decay, infestation and mould growth [13,15,22].

Limecrete floors are considered a safe solution to improve the energy performance of solid ground floors, and/or to repristinate their original thermo-hygrometric behaviour [13]. Lifting and reinstating the solid ground floor finish, could be possible without damaging it. However, the complexity of such task makes it a high-risk option and a preferred choice when the floor finishes are not of historic value [14,15,22].

Timber ground floors can be insulated between the joists using vapour-permeable materials [13]. This solution, however, is also considered a high-risk one, applicable mainly when the floor-boards are not of historic value as their removal can lead to damage of the old timber-boards and irreversibly alter the characteristics of the original flooring [15,24].

Ceilings. Insulating intermediate ceilings has been excluded as an option in this study because the adjacent dwellings, all occupied and heated, are assumed to be in adiabatic conditions with the dwellings investigated [33]; therefore, no heat exchange takes place between the simulated models and their adjacent properties.

Roof. Loft insulation is unanimously considered, by conservation bodies, a low-risk option for pitched roofs, when the loft is not a habitable space, being the simplest, cheapest and most straightforward approach [5,6,12,13,14,15,16,20,27,29,30,49]. In fact, it does not involve the costs and disruption caused by insulating between rafters or renewing external roof finishes and the risks for the aesthetic character of the elevation, associated with raising the level of the finished roof. Ventilation should always be considered to reduce moisture risk [12].

Insulating at rafter or ceiling level is considered a medium-risk option, respectively for pitched (when the loft space is habitable) [15] and flat roofs [15,19]. It requires skilled workmanship, especially when historic ceilings are in place, to ensure that they will not be damaged [12].

Insulation above rafters and above flat roofs raises the level of the finished roof, which may often be non-permissible, therefore it is considered a high-risk option. It might still be applicable, as long as the finished roof level does not unacceptably alter the rhythm of the adjoining terraced houses and if the loft space is habitable [15,19,21,13].

Insulation below rafters (for pitched roofs) and below ceiling level (for flat roofs), while compromising internal historic finishes if in place, reduces the internal height, which is already limited in the dwellings investigated. Therefore, this option has been excluded in this study as it would unacceptably compromise the usability of the internal space [15,19,21,13].

For all the solutions, a careful design and detailing, as well as the appropriate choice of materials, are of uppermost importance, in order to avoid risks of interstitial condensation [12].

External walls. New permeable renders and External Wall Insulation (EWI) have been excluded as retrofit options for both front and back elevations of all the CSs selected, as they would alter the exterior in thickness and, potentially, in color. This would imply a significant change in external appearance, when applied on one single unit within a row of terraced houses [12] and is certainly unacceptable for individual dwellings, occupying just one floor, within a grand terrace of houses.

Internal Wall Insulation (IWI), is a particularly delicate intervention, whose impact must be first carefully assessed against the heritage value and moisture balance of the construction [5,6,8,12,13,14,15,16,23,27,28,29,30]. Different solutions should be considered for walls, depending on the type of internal finishing.

Most of the front walls, in the selected CSs, are internally finished in plaster on lath. Whenever the room presents decorative elements, such as mouldings and stucco or timber works, in the form of cornices, dados and skirtings, IWI is generally not allowed, with the exception of loose insulation blown behind plaster on lath (considered a medium-risk option). The latter, in fact, does not alter the internal finishing or overall proportions [6,12,13,15,23].

Alternatively, the high-risk option potentially permissible can be the use of high-performance thin insulation materials [50,51] on the internal face of the wall. In this case, very limited change in thickness is recommended, not to alter the internal proportions, and in order to keep the decorative elements in place, because removing and reinstating them could pose risks to their integrity [15]. An added thickness of maximum 20mm could potentially be permissible, if justified by a sensible improvement in the thermal performance of the construction (Interview with C.O., 12/12/2019).

For walls without decorative elements, finished in plaster on lath or solid, an alternative high-risk option could be the use of other insulation materials (in boards, batts, or rolls), directly fixed to the internal wall's face or using timber battens, balancing the need for energy improvement, with the loss of internal space and proportions, and the risks of condensation. The literature considers natural materials as the most applicable for traditional buildings and recommends their use. Indeed, they are the closest to the original materials and constructions, highly breathable by nature and suitable for totally reversible types of applications, available in different forms, capable of achieving thermal performance similar to that of oil-derived materials but also much safer to install, requiring minimal protective clothing and being totally eco-friendly, biodegradable and recyclable [13,16,35].

When the internal finish is plaster or plasterboard, the use of insulating plaster has been proposed as medium-risk option (after removing any plasterboard eventually in place) [13,15]. Alternatively, the high-risk option also for solid walls is the use of high-performance thin insulation materials, that maximise the use of internal space, while providing very good thermal resistance [50,51].

If applicable without compromising the heritage value of the dwelling, any type of IWI, must be carried out providing careful detailing and using qualified contractors to avoid the risk of unintended consequences [12,13,14,15,23], which can be particularly high for this intervention [35,52,53,54].

4.2 Future work

The solutions defined this way, are then utilized in the following stage of research to model new building elements. This will be done modifying the envelope of the base-cases, according to the new materials build-ups that will be devised for each intervention, aiming to achieve the target U-value imposed by the current Building Regulations for each element of the thermal envelope. Such material build ups will then be assessed to ascertain the risk of interstitial condensation. Then, the new retrofitted elements will be applied to the base case models to assess the reduction in energy consumption associated with space heating, and corresponding CO2 emissions, by means of DES. Finally, a sensitivity analysis, will aid to assess the efficacy of the measures selected, individually or in combination with other measures, to help devise a framework for sensible, safe and effective energy retrofit interventions.

5 Conclusion

The paper provides a tool that supports the decision process for the selection of applicable sensible interventions for TLDs aimed at the assessment of their effectiveness in reducing heating energy consumption, therefore improving their environmental impact. The approach proposed, devised from the critical review of literature, stems from a clear understanding of the heritage value of the building, as well as of the behaviour of its traditional construction. It aims to address the need for a validated energy retrofit strategy for TLDs, characterised by the choice of individual measures, that take into account the specific listed building value, conserving and enhancing the original features of the dwelling, while ensuring that the change operated does not adversely affect the thermo-hygrometric balance of its construction and improves the thermal performance of the envelope.

The methodological approach devised for this study builds upon that already taken by previous UK, EU or international projects (e.g. CALEBRE, 3encult, Effesus, RIBuild) [55,56,57,58]. Stemming from a similar approach to retrofit to that of the of the CALEBRE project (aiming at improved air tightness and U-values of the external envelope), it filters the range of measures selected through the identification of the specific heritage values to be protected in each CS and the impact assessment of each measure on such values (similar to the 3ENCULT and EFFESUS projects) to come up with a list of sensible measures. The devised methodology then applies a further filtering of the measures selected, assessing the associated mould growth potential (as in the CALEBRE and RIBuild projects) to obtain the sensible-and-safe range of measures and determine in detail materials build ups for each of those. Finally, it assesses the effectiveness of the interventions devised, by measuring their impact on energy consumption and associated CO_2 emissions by means of DES (as in the CALEBRE and 3ENCULT projects).

This strategy contributes to the novelty of the study, through a trade-off between the need for individual solutions - accounting for the complexity of all factors involved in each dwelling - and the necessity of consistency in the rationale behind the choice of interventions and materials.

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