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Simulation of Heritage Buildings: The Duke of Bedford's Cottages in West Devon

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Abstract

Building performance simulation (BPS) is used to select and justify an energy-saving retrofit for the Duke of Bedford's cottages, aiming to improve performance sufficiently within the cottages' constraints, which include conservation concerns plus wider practical and economic constraints. Building data is passed from a building information model (BIM). Building energy simulation (BES) and hygrothermal modelling obtain results in the performance attributes of energy efficiency, thermal comfort and damp risk. Parametric analysis assesses performance ranges and sensitivity to long-term climate uncertainties. Moderate fabric upgrades, including window replacement and an insulating plaster, perform best within their constraints. Long-term, a heat pump is recommended to increase efficiency though is currently financially constrained. Ultimately, this sufficiently balances performance and heritage needs.

Key innovations

- Uses a novel approach to retrofit energy saving measure selection using BPS and parametric analysis to assess success on heritage buildings.
- Applies parametric climate adaption analysis to the cottages to ensure that retrofit energy saving measures stand the test of time.
- Provides a successful case study of building performance simulation techniques and theory being applied to a building vernacular with specific constraints containing, a methodology that can be applied to other heritage buildings.

Practical implications

Using this methodology, building professionals are able to better appraise retrofit measures when faced with heritage vernaculars with complex and specific needs, meeting the need to retrofit millions of homes by 2050.

Introduction

UK homes are much older than rest of Europe, with pre-WWII dwellings well exceeding the USA, Germany or France (BRE, 2008, p. 45). Indeed, of twenty-five million homes in need of retrofits (RIBA, 2020a), five million are pre-1919 (MHCLG, 2020b). These are non-homogenous, facing unique combinations of constraints. Bedford's cottages are one pre-1919 vernacular, with almost 300 built in West Devon between 1842 and 1866. A key remnant of Tavistock's stannery history (Brayshay, 1982), many cottages in the town are now Grade-II listed (Historic England, 1977) and part of Cornwall and West Devon's Mining Landscape World Heritage Site (WHS) (UNESCO, 2006). Other than largely unsympathetic alterations and degradation, today quite little has changed.

Though impressive heritage assets, this means Bedford's cottages fail to meet modern thermal performance requirements. This requires a retrofit energy saving measure (ESM), where works would take place to the cottages to "improve the energy performance (…) by saving or generating energy" (BSI, 2020, p. 5). Many interest groups exist for this. Cottage residents seek a reduction in energy bills and improvement in thermal comfort, alleviating the issue of fuel poverty. This issue, which disproportionately affects older buildings (DBEIS, 2020a, p. 70; MHCLG, 2020b, p. 14) is also a policy concern at national (*ibid.*), county (Devon Community Foundation, 2019) and local levels (TEC, 2019) and means improving retrofit applications to heritage buildings carries real social benefit. Policy interests extend to planning, with the local council seeking to "protect, enhance and promote the cottages" (WDBC et al., 2019, p. 213). Other interest groups exist in the third sector. Tavistock Townscape Heritage Initiative seeks "repair and reinstatement" (WDBC and TTC, 2014, p. 29), while the Tamar Energy Community (TEC) began the *Warmer Bedford Cottages* project to "cost-effectively enhance" dwellings (TEC, 2019). The TEC asserts that an ESM application would need to maintain and renovate the cottages, plus increase insulative performance with the objective of reducing energy use and preserving the cottages (TEC, 2020, p. 8). Damp risk too must be eliminated. Needs then ultimately sit in two categories: enhancing performance as homes or preserving heritage.

To a large extent, these needs conflict, creating a problem. Firstly, heritage. Challenges in retrofitting dwellings are augmented when dealing with heritage buildings such as Bedford's Cottages, facing additional constraints owing to their listed status and other cultural designations. Upgrades to the thermal envelope by adding insulation is a significant process that will materially alter the building and attract heritage concerns. Preserving heritage would avoid such drastic changes to the buildings but impede sufficient retrofit for energy use reduction and thermal comfort. The *Venice Charter* describes "limits" on "social use" (ICOMOS, 1964). Webb (2017, p. 755) agrees, identifying conservation and energy consumption as "dominant" but "competing" criteria in historic buildings.

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Constraints also exist for this specific vernacular. Bedford's cottages are small, with added insulation reducing usable floor area. This compactness means heat loss form factor is higher, compounding insulative requirements. Poor condition adds other vulnerabilities, being exposed or even worsened by the required work. Unauthorised work or extensions (WDBC and TTC, 2014, p. 37) also demands measures be versatile, but this work itself is aging, requiring its own specific treatment.

Volume matters. While Bedford's cottages are just a few hundred, millions of its contemporaries require ESMs. Its conservation requirements are important safeguards, but at this scale make meeting the mammoth retrofit need no easier. A blanket approach may hasten progress, but at the expense of heritage assets within housing stock and reliability, given the bespoke nature of heritage buildings.

Finally, though the decarbonisation need may be met, the effects of climate change are not completely preventable. Some level of mitigation and adaption is necessary to prepare for more extreme and warming weather in the coming decades. CIBSE (2020, pp. 19–6) describes climate change as having large implication for thermal performance. Hot summers will be the norm, and temperature change by 2070 could be as high as 5.4 °C in summer and 4.2 °C in winter for a high emissions scenario, causing homes to overheat (Met Office, 2019, p. 6) and very permanent changes to improve insulative performance requiring reversal or added cooling systems.

Contradictory and changing requirements among stakeholders and interest groups suggest a somewhat wicked problem: with no optimal solution achieving everything and instead demanding careful compromise and a rigorous evidence-set to enhance decision making. This paper therefore aims to use BPS to select and justify an ESM to improve thermal performance enough to meet modern requirements, within unique heritage constraints.

Literature review

Present issues in energy-saving retrofit applications

Insulation of solid walls has been found to make large performance increases, even outperforming twentieth century cavity walls (Ferreira, Pinheiro and Brito, 2013; Goodhew, 2016, p. 104). This does attract some risk however, needing to "prevent condensation occurring" or use a moisture-permeable design (Historic England, 2016, pp. 10–16), otherwise seeing damage to the building fabric and performance degradation. Concerns also exist around excessive insulation, with CIBSE's *Guide L* describing a risk of "degrading" building fabric and overheating (CIBSE, 2020, pp. 9–18). Insulative quality is vital (Borgstein, Pakenham and Raja, 2011, p. 5), alongside careful planning.

Age-specific constraints would affect Bedford's cottages, such as risk of decay, harm and loss of heritage (STBA, 2015, pp. 12–13). Frameworks have emerged to deal with this work: Historic England categorises measures by the degree of risk or cost associated (Historic England, 2018, p. 25) while *PAS-2035:2019* places measures in three risk groups (BSI, 2020, p. 38). Three domains of risk exist: "energy and environment", "building health" and "heritage or community", underscoring its breadth the (STBA, 2015, p. 6) and positioning risk as an essential and complete concept in retrofit ESM planning. Risk management in retrofit supports meeting international conservation needs, such as those in the *Venice Charter*. This instates the need to protect heritage on a "permanent basis", being "socially useful" (such as residential use) and "preserving… historic value" (ICOMOS, 1964) For cottages protected within a WHS, this is most relevant.

The "whole building approach" is another such concept (STBA, 2015, p. 4; Historic England, 2018, p. 9), where measures are assessed in their fullest context considering "interrelationships" between systems and fabrics (*ibid.*). This contextual approach begins to address sustainability concerns too (Goodhew, 2016, p. 103), though arguably undermines the speed of implementation being so systematic and rigorous.

Interoperability between BIM and BPS

BIM, and specifically Historic-BIM has already been identified for option appraisal and simulation (Daniotti et al., 2020, pp. 391–398), with interoperability facilitating the latter, a key criterion among in selecting BPS tools (Attia et al., 2012, p. 167). This involves in transferring building information from BIM models into a BES tool, facilitated by data exchange standards such as gbXML and Industry Foundation Classes (Chen *et al.*, 2018, pp. 137–138). This is generally effective, although different degrees of compatibility exist, with issues persisting in how much data can be transferred (*ibid.*). Given that data would only otherwise need to be recreated in a BPS tool, even incomplete interoperability is considered useful.

The performance gap in heritage buildings

Roy and Oberkampf (2011, p. 2131) argue there is a "fundamental disconnect" between simulation and practical applications, elsewhere described as a "performance gap" (de Wilde, 2014), with discrepancies between simulated results arising from uncertainties in modelling. To some extent this is "inherent" as uncertainties can never be fully controlled (*ibid.*), however its manifestation varies for retrofit applications: sometimes achieving an "ambitious target" but elsewhere suffering "substantially" from this (Baeli, 2013, p. 126).

Tian *et al.* (2018, pp. 7-12) identified these uncertainties:

- weather, with weather files based on historic data, not accounting for variations particularly in the long-term;
- the building envelope, affecting physical processes;
- HVAC system, which may not operate in "ideal conditions" or be as efficient as modelled; and
- occupant behaviour, with human behaviour affecting thermal performance.

Epistemic uncertainties (Helton *et al.*, 2010, p. 605) are a particular issue for heritage buildings, with uncertainties in construction typical in built constructions that lack plans and construction documentation (Roy and Oberkampf, 2011, p. 2132) but even more so given time elapsed. Age and degradation will affect the building fabric's thermal properties, while appropriate measured data is lacking and a specific issue (Webb, 2017, pp. 752–755). Modelling itself attracts "abstraction" uncertainties from "simplifications or concessions" in modelling (MacDonald, Clarke and Strachan, 1999, p. 1). To avoid such gaps, effective modelling must firstly be ensured, adequately validating, verifying and calibrating models to assure trust in their results (Roy and Oberkampf, 2011).

For aleatory uncertainties, parametric analysis using probabilistic changes in variables can be used to measure their impact and assess confidence, determining "dependability" of a model's output (Eisenhower et al., 2012, p. 171). Such probabilistic methods can also be applied to climate change (Met Office, 2019), with impacts measured through varying climate excitation during BES, using probabilistic files such as *PROMETHEUS* (Eames, Kershaw and Coley, 2011). Some caution must be applied to this however, as climate adaption analysis fails to address other uncertainties that arise over long timescales: changes in "fuel mix", heating system, and building operations being a few assumptions held constant by climate adaption models (de Wilde and Tian, 2011, p. 3017; de Wilde et al., 2008). Programmes applying climate adaption analysis methodologies such as the *Design for Future Climate* project reported mixed success, sometimes being informative but sometimes being unviable (BRE, 2012a, p. 9), with "concept stage" implementation being vital (*ibid.*, pp. 41–42).

Drivers affecting retrofit adoption

Retrofits to heritage buildings share many drivers with standard retrofits. Energy efficiency targets exist, with the *Clean Growth Strategy* seeks to "upgrade as many houses to EPC Band C by 2035", though caveated with the target applying only where "practical, cost-effective and affordable" (BEISC, 2019, p. 13). Conditions for state funding of measures also shapes design, with the UK government part-funding of retrofit ESMs in the autumn of 2020 (HM Treasury, 2020). Similar schemes exist elsewhere. ESMs come with a "golden rule" and are only considered financially viable if the return on investment exceeds capital cost (Hopfe and McLeod, 2015, p. 284). Of course, there are other factors and externalities affecting ESM decision making, something this arguably oversimplifies, though underscores the important relationship between savings achieved, initial outlay and willingness to invest. ESMs assessed for Bedford's cottages must therefore make large enough savings to recover the initial investment in good time.

Methods

To fulfil the research aim and meet the needs of stakeholders, three performance attributes are simulated (energy efficiency, thermal comfort and damp risk) spanning two simulation domains: hygrothermal modelling and BES, each ESM was evaluated in their respective tools, WUFI Pro 6 and DesignBuilder. From results and discussion in the context of wider performance attributes such as cost and conservation, a preferred option will be developed. The need to represent a range of cottage designs, including both brick and rubble stone constructions was balanced with available building information and access. Sampling included mid- and end-of-terrace designs, appreciating reduced energy loss by party walls. Selected were two cottages at Dolvin Road and two at Westbridge, labelled A-F according to their position. Some alterations have taken place, including single-story rear extensions and new upstairs bathrooms. Gross internal area ranges from 59.6m^2 to 81.6m^2.

System Description

A repository of building information and geometry was obtained from the TEC. To support its input in DesignBuilder and create usable building information data, Autodesk Revit 2020 was used to create a building information model (BIM), seen in Figure 1. Use of gbXML to exchange data ensured efficient use of modelling time and enhanced the acquisition of data, reducing abstraction uncertainty. After verification, several enhancements took place to ensure a representative model. Party walls were assigned as adiabatic boundaries, neighbouring cottages were included as shading groups and rooms were assigned to individual zones, with the appropriate schedules. Heating system was also modelled, with cottages using a combination of gas boiler systems, electric immersion heaters, fan heaters, stoves or open fireplaces for heat.

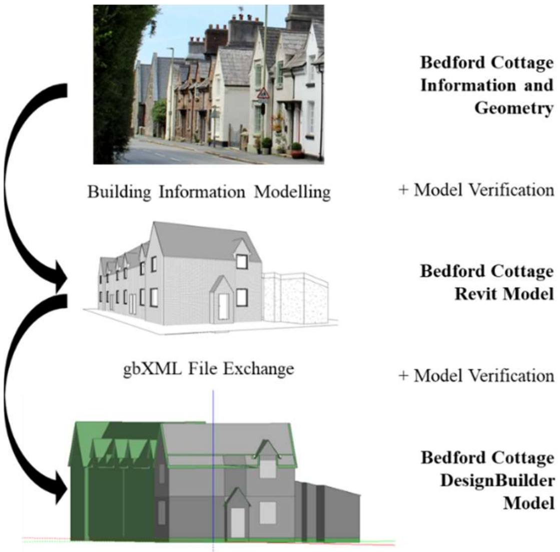


Figure 1: Process of Describing the Bedford Cottages in DesignBuilder using AutoDesk Revit and gbXML

For hygrothermal modelling, building information and hygrothermal properties for the walls was inputted into WUFI Pro, along with shading and exposure information.

System Excitation

Modelling dealt with limited information concerning occupant behaviour. Standard activity templates and schedules were therefore used for a typical domestic dwelling in the UK. A setpoint temperature of 18°C and a setback temperature of 12°C were applied. Local weather data was obtained for neighbouring Bodmin, a similar edge-of-moorland, non-coastal town.

Measurement Protocol

Performance measures (PMs) were selected from the chosen attributes. For energy efficiency:

- PM_1: Specific Site Energy Use [$kWhm^{-2}a^{-1}$]
- PM_2: As PM_1, of which for Heating [$kWhm^{-2}a^{-1}$]
- PM_3: Specific Zone Heating [$kWhm^{-2}a^{-1}$]

For thermal comfort:

- PM_4: ASHRAE Standard 55-2013 (ASHRAE-55) Uncomfortable Occupied Hours per Annum (90% Acceptable) [%]
- PM_5: ASHRAE-55 Uncomfortable Occupied Hours per Annum (80% Acceptable) [%]

For damp, relative humidity and air temperature will be plotted against limiting isopleths *Lim B I* (for degradable substrates) and *Lim B II* (for porous substrates), giving mould growth risk as a booleon result.

Runtime Control

For BES, hourly data will be obtained for one calendar year. Hygrothermal modelling is run over five years.

Framework for Analysis

ESMs concern a change in design or system to improve thermal performance. Such changes will be represented as independent design variables, with analysis to determine how this affects performance in each of the performance measures. Percentage change is given to compare to a baseline (current condition). Parametric analysis is used alongside simulation of specific ESMs to assess sensitivity to design variables using regression analysis. The same methods are also used to assess climate variability over time, with climate excitation varying using probabilistic weather information from *PROMETHEUS* (Eames, Kershaw and Coley, 2011).

Foreseen Issues and Problem Mitigation

Correct model implementation was ensured through a process of verification and validation. Care was taken to avoid errors in data transfer and software errors, with model debugging occurring in both Revit and DesignBuilder. Occupant behaviour is typically a large uncertainty in BES, with it being unclear when non-scheduled heating equipment such as stoves were used. The TEC acted as an important feedback loop having engaged with residents directly and conveyed that fuel poverty among residents often led to rationalisation of heating, favouring these stoves. While the model cannot fully appreciate this behaviour and with building monitoring being unpractical during the COVID-19 pandemic, this will instead be appreciated in discussion. To facilitate calibration in these circumstances, householders had provided energy bills in a survey for the TEC, determining that results fell in the expected range.

Results

Baseline Cottages

Table 1 provides results for the baseline cottages, with Westbridge F being the most energy intensive, and Westbridge C being the most thermally uncomfortable.

Energy from the cottages is lost in three ways, with results provided in Table 2. Most losses through the opaque fabric are attributable to the walls of the building, averaging 57.8% of losses and the floors, at 29.1%. Ventilation losses are large for the cottages. Window losses are low despite being single glazed for most of the cottages, owing to small area and secondary glazing.

Table 1: BES Results for the Baseline Cottages

Performance Measure	**Dolvin E**	**Dolvin F**	**Westbrideg C**	**Westbridge F**
PM_1 ($kWhm^{-2}a^{-1}$)	176.4	209.8	216.0	227.0
PM_2 ($kWhm^{-2}a^{-1}$)	120.3	162.2	163.0	170.0
PM_3 ($kWhm^{-2}a^{-1}$)	102.2	137.9	138.5	125.6
PM_4 (hours)	980	1023	1095	838
PM_5 (hours)	689	762	871	579

Table 2: Energy Losses for the Cottages [kWh]

Heat Loss Component	**Dolvin E**	**Dolvin F**	**Westbrideg C**	**Westbridge F**
Windows	-795.6	-1027.2	-654.3	-544.8
Ventilation	-3275.1	-3850.8	-2353.8	-2644.2
Opaque Fabric	-8408.3	-12794.1	-8910.3	-9754.2

Parametric Analysis

Table 3: Regression Analysis for Site Energy Use [kWh]

Design Variable	**Dolvin E**		**Dolvin F**		**Westbrideg C**		**Westbridge F**	
	SRC	p	SRC	p	SRC	p	SRC	p
Int.	0	0	0	0	0	0	0	0
1	-0.46	0	-0.24	0	-0.29	0	-0.39	0
2	-0.38	0	-0.43	0	-0.44	0	-0.53	0
3	-0.13	0	-0.16	0	-0.07	0.30	-0.19	0
4	-0.42	0	-0.49	0	-0.58	0	-0.37	0
5	0.02	0.60	0.03	0.54	0.03	0.68	-0.04	0.20
6	-0.04	0.24	-0.04	0.43	-0.10	0.16	-0.03	0.32

Table 4: Regression Analysis for ASHRAE-55 Uncomfortable Occupied Hours per Annum (90%) [hrs]

Design Variable	**Dolvin E**		**Dolvin F**		**Westbridge C**		**Westbridge F**	
	SRC	p	SRC	p	SRC	p	SRC	p
Int.	0	0	0	0	0	0	0	0
1	-0.63	0	-0.31	0	-0.61	0	-0.47	0
2	-0.43	0	-0.52	0	-0.48	0	-0.51	0
3	-0.21	0	-0.24	0	-0.1	0.16	-0.23	0
4	0.05	0.08	0.09	0.08	0.08	0.29	0.14	0
5	0.01	0.83	-0.06	0.24	-0.04	0.5	-0.08	0.01
6	-0.02	0.54	-0.02	0.66	-0.08	0.24	-0.06	0.04

With results for the baseline cottages, parametric analysis took place using the following design variables:

1. Floor Insulation (from uninsulated to superinsulation)
2. Wall insulation (from uninsulated to superinsulation)
3. Roof insulation (from uninsulated to superinsulation)
4. Heating system (from gas boiler to heat-pump)

5. Window covering (from no blinds to heavy blinds)
6. Window system type (from single- to triple-glazed)

Optimisation variables were PM_1 and PM_4, capturing both attributes. Results follow in Table 3 and Table 4, giving standardised regression coefficients (SRC) and P-values.

This analysis demonstrated that floor and wall insulation had a statistically significant ($p < 0.05$) effect for all cottages, both for energy efficiency and thermal comfort. Roof insulation had a smaller but still statistically significant effect for all cottages except Westbridge C. Pareto-optimised solutions were identified for the PM_1 and PM_4, and all had the design variable selection of an air source heat-pump and superinsulated walls.

ESM selection

These findings led to the following ESMs being selected:

1. Thermal fabric upgrade (Diathonite Thermactive plaster, double glazing and Geocell floor insulation).
2. Thermal fabric superinsulation (extruded polystrene high performance insulation and triple glazing).
3. Window upgrade only to double glazing.
4. Installation of an air source heat pump.

These were simulated in DesignBuilder, achieving the performance given in Table 5, and saving in Table 6.

Table 5: Average Performance in each PM

Performance Measure	ESM 1	ESM 2	ESM 3	ESM 4
PM_1 ($kWhm^{-2}a^{-1}$)	126.9	70.9	207.7	112.3
PM_2 ($kWhm^{-2}a^{-1}$)	78	22.2	154.1	70.2
PM_3 ($kWhm^{-2}a^{-1}$)	64.4	18.2	126	126.34
PM_4 (hours)	788	990	1031	996
PM_5 (hours)	494	752	748	711

Table 6: Average Change in each PM

Performance Measure	ESM 1	ESM 2	ESM 3	ESM 4
PM_1 ($kWhm^{-2}a^{-1}$)	-39%	-65.9%	-0.3%	-46.1%
PM_2 ($kWhm^{-2}a^{-1}$)	-49.6%	-85.6%	-0.3%	-54.6%
PM_3 ($kWhm^{-2}a^{-1}$)	-49.4%	-85.7%	-0.9%	-0.6%
PM_4 (hours)	-19.9%	0.6%	4.8%	1.2%
PM_5 (hours)	-31.9%	3.7%	3.1%	-1.9%

Simulations found that ESM 2 made the largest energy efficiency improvement across the sample cottages, while ESM 1 made the largest improvement in thermal comfort. Window replacement was found to have little impact.

Climate Adaption Simulation

This first investigated change in zone heating demand under two scenarios (medium and high emissions) with probabilistic weather files from *PROMETHEUS* (Eames, Kershaw and Coley, 2011). Results follow in Figure 2.

Summarising ESM performance, simulation results found ESM 1 improved energy efficiency and thermal comfort compared to the baseline under both scenarios. ESM 2 improved energy efficiency even further, however dramatically increased thermal discomfort due to overheating. ESM 3 made marginal improvements to energy efficiency and thermal comfort. ESM 4 did not affect heating demand but improved thermal comfort.

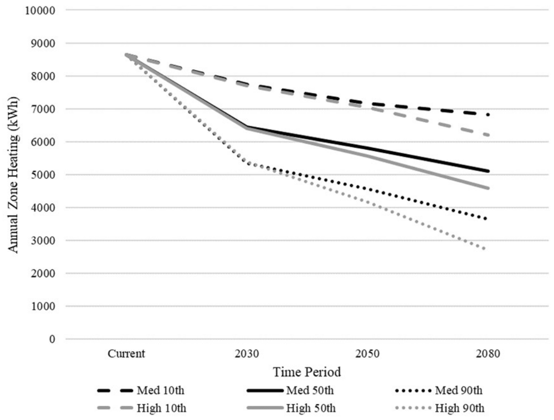
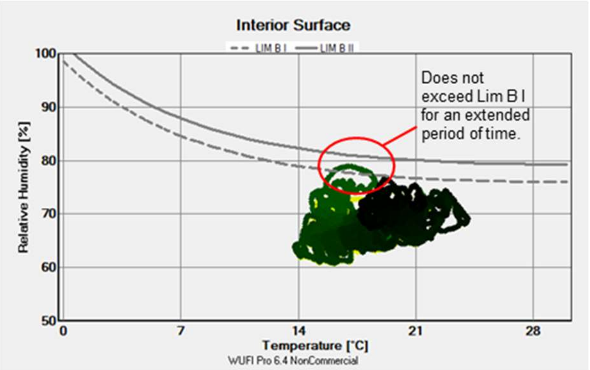


Figure 2: Average Zone Heating for the Cottages applying *PROMETHEUS* Weather Excitation

Hygrothermal Modelling

One dimensional models of each wall were created for the baseline and ESMs. Relative humidity and temperature at the interior surface were plotted for each wall (Figure 3),

Figure 3: Relative Humidity and Temperature for the South-East Facing Dolvin Cottage Wall



Each plot was inspected to see if the limiting isopleths were exceeded for a sustained period; this does not in Figure 3 and therefore no mould growth risk is expected.

Table 7: Mould Growth Risk

	Orientation	Baseline	ESM 1	ESM 2
Dolvin	North-East	False	False	False
	South-East	True	False	False
	South-West	True	False	False
	North-West	False	False	False
Westbridge	North-East	True	False	False
	South-East	True	False	False
	South-West	True	False	False
	North-West	True	False	False

This found that mould growth risk was currently likely on the walls in at least two orientations for the cottages. Both insulation measures (ESM 1 and 2) would prevent mould growth on the interior surface. While ESM 3 does not affect the interior walls, consultation with the TEC identified that cold bridging and condensation was problematic, with window upgrade likely to reduce this.

Discussion

Current performance of the Bedford Cottages

Baseline simulation in the BES tool found the opaque fabric of the cottages caused much of the heat loss, and therefore insulation of these components would be essential. This finding was verified by regression analysis of parametric simulations, which found that floor, wall and roof insulation (design variable 1, 2 and 3) all had a statistically significant effect on both energy efficiency and thermal comfort. This found strong statistical significance between the two attributes and three design variables. The regression coefficient identified during parametric optimisation also supported the large performance increases offered by wall insulation identified in the literature review (Ferreira, Pinheiro and Brito, 2013; Goodhew, 2016, p. 104). Floor insulation was similar, being statistically significant for both attributes and for all cottages, with regression coefficients nearing that of wall insulation. For all but Dolvin E, wall walls caused the largest proportional heat loss. With a larger heat loss area, end-of-terrace cottages saw larger transmission through the opaque fabric than their mid-terrace counterparts, with such properties particularly benefitting from ESMs. Hygrothermal simulation agreed with qualitative feedback from residents to the TEC that mould growth was an issue on the external walls. This was found on all orientations for the Westbridge Cottages and the south-facing orientations for those at Dolvin Road.

Across cottages, thermal discomfort was high owing to low operative temperatures, correlating with the high heat loss. ASHRAE-55 found the cottages would be thermally uncomfortable for 2.7 occupied hours per day on average, at a 90% acceptability. Rationalisation of heating due to fuel poverty clearly exacerbated thermal discomfort, with residents trading thermal comfort for affordable heating, hence the cottages are not more energy intensive.

In operation, the cottages were found to be expensive to heat for their size. One cottage, without central heating, is particularly expensive due to reliance on electric heaters. Cottages were benchmarked against Ofgem's (2020) *Typical Domestic Consumption Values*, which found that despite being the cottages small size, consumption of gas alone neared levels for a medium-sized household. For the environmental view, this high energy consumption by the cottages also leads to high operational carbon use.

Reflection on ESM retrofit options

ESM 2 best improved energy efficiency its three component PMs. The worst performing result was ESM 3 meanwhile saw the smallest improvement in PM_1 and PM_2, while ESM 4 failed to reduce heating demand at all. This was maintained during climate adaption modelling.

For thermal comfort, ESM 1 improved performance in both PM_4 and PM_5, while ESM 3 increased discomfort.

ESM 1 moderately insulated the thermal fabric, seeing large reductions in fabric losses and therefore improving performance in the attribute of energy efficiency, reducing heating demand by an average of 49.4%. Climate adaption modelling demonstrated that these performance improvements would be maintained under the expected change for medium and high emissions scenarios, faring best out of the four options.

Hygrothermal simulation of the walls found that ESM 1 and 2 were likely to eliminate damp risk. ESM 3 and 4 did not deal with the building's opaque fabric so were not modelled, nor will they make a significant improvement in this attribute, other than the reduction of cold bridging through the window upgrade in ESM 3.

ESM 2 made the largest saving, reducing zone heating by over 85%, however is rightly and easily excluded for being so distant from the realities of a heritage building. While design variable optimisation correlated reduced energy use and increased thermal comfort, this did not materialise for ESM 2, best reducing energy use but overheating the cottages and causing discomfort.

For thermal performance, ESM 3 was found to be insufficient on its own. Regression analysis supported this assessment, finding that iterations on window performance would not have a statistically significant effect on energy use. Double glazing would however help eliminate condensation, cold bridging and damp, despite attracting a large degree of risk to heritage. This may be combined with insulated window coverings to make further small improvements, with more simulations finding that this would make a marginal gain. The cottages currently had received some double glazing, although secondary glazing was more common. Replacing secondary windows with double glazing still made energy savings, supporting findings by English Heritage (2009). Ultimately an inspection of windows is needed to determine their condition and how necessary a replacement is. Well-designed wooden double glazing however is likely to be preferable to single-glazed windows left in a state of disrepair and affixed with uPVC secondary glazing, or indeed over some current “unsympathetic” uPVC windows identified locally (WDBC and TTC, 2014, p. 23), agreeing with the objective of “reinstatement” (*ibid.*, p. 29). Implementation of double glazing must however be carefully balanced with the arising conservation concerns.

ESM 4 finally made impressive reductions in energy use due to the highly efficient heating system, with the potential to reduce carbon use as the electricity supply becomes more renewable with time. Savings were nearly as dramatic as ESM 2, with no need to add insulation or interfere with the thermal fabric, therefore attracting much lower risk to heritage but still making large carbon savings under SAP 10.1. This option will not any significant improvement to the third performance attribute of damp risk, which will persist due to cold bridging, therefore making it necessary to combine this with other upgrades to the properties, such as wall insulation and remedial repairs.

Assessment of risk

ESM 1 attracts a fair degree of risk, however the moisture-permeable design is supported by Historic England's guidance (2016, pp. 10–16), and so long as these are carefully implemented, limiting thermal bridging where possible and maintaining insulative quality, then this risk can be managed and accepted (Borgstein, Pakenham and Raja, 2011, p. 5). Hygrothermal modelling demonstrated that this option would eliminate mould growth risk.

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ESM 2 attracted the highest degree of risk, would not be moisture permeable per heritage constraints (Historic England, 2016, pp. 10–16) and performed worst in the climate adaption analysis, overheating as time went on. Superinsulation would come at large cost to historical value. Currency of ESMs is important, with a danger that superinsulation now will impede performance in the future and attract further risk, seeing this ESM excluded.

Financial Concerns

Large savings in heating demand would help shorten the payback time and enhance financial viability for residents (Hopfe and McLeod, 2015, p. 284). Residents are likely to value operational cost reductions over marginally more sustainable materials, and although the latter is important (CIBSE, 2020, pp. 12–1; Balson, Summerson and Thorne, 2014, p. 10). Given that ESM 1 and 2 evidenced large energy savings while maintaining affordable gas central heating, both would be desirable for cottage owners – although the latter is unfeasible due to heritage concerns.

The change to more expensive electricity supply for cottage residents using an air source heat-pump keeps such a system out of reach. This will therefore remain financially unviable for some time as the price of electricity will continue to outpace the price of gas, increasing operational costs and meaning initial investment would not be repaid, contradicting the “golden rule” of ESM viability (Hopfe and McLeod, 2015, p. 284). While there is therefore little incentive to implement this in the short-term, state incentives may soon make the financial context much more favourable (DBEIS, 2020b).

The preferred option

Owing to findings from BES and hygrothermal modelling, synthesised with wider performance attributes including cost and conservation, it was decided in the short term to implement ESM 1 and insulate the building fabric. ESM 2 was constrained by the building’s heritage while ESM 3 alone would not sufficiently reduce energy use to overcome issues such as fuel poverty and the condition of the cottages. As heat pump incentives emerge in the future, ensuring affordability, ESM 4 will then be implemented to make further performance improvements, though this is not financially feasible in the short term.

Conclusion

This paper sought to use BPS to select and justify an ESM to improve thermal performance enough to meet modern requirements but doing so within unique heritage applied to a specific vernacular. Ultimately, this found that BPS, in both the domains of heat and moisture and energy performance, was an appropriate method to evaluate retrofit ESMs for heritage buildings and is an activity within the reach of building professionals. Findings from BPS were able to include and exclude energy retrofit options and be synthesised with conservation, socioeconomic and environmental concerns. This may help overcome the wicked problem of retrofitting heritage buildings: creating an enhanced brief of drivers affecting retrofit decision-making, using a BIM to organise limited data into useful information, creating an interoperable transient model, controlling uncertainties and synthesising results with the original brief of drivers to create a preferred option. The production of this paper enhanced information about the cottages’ performance, which alongside work by the TEC and other stakeholders should make a profound improvement in the condition of the cottages and their quality as homes, with results offered back to these stakeholders for review and use in their own work and policymaking ahead of retrofit.

The following further opportunities have been identified:

- To conduct further research into thermal fabric uncertainties in heritage building using measured data, including detailed metering and heat flux monitoring. Such a lack of data for thermal properties has been identified as a major limitation in literature and makes deviations from design U-values likely (Webb, 2017).
- To measure the performance improvement in use after the selected ESM has been applied to the cottages, using measurement and verification to assess success
- To use monitoring and targetting (M&T) to address any deviations in performance (or “performance gaps”) and assure that ESMs achieve their full potential as designed (de Wilde, 2014).
- To create case studies that implement this methodology for other precedents and vernaculars to understand good and poor practice for historic building retrofit within a wider pool of vernaculars.

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