# The establishment of a whole house analysis framework and process to design out unintended consequences in the energy retrofit of small-scale domestic traditional buildings

Neil Richard Golding

Supervisor: Bruce Induni

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**Candidate's ID Number:** 1766577

**Candidate's Surname:** Golding **Candidate's Full Forenames:** Mr Neil Richard

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## (i) Abstract

The United Kingdom has an estimated 29 million dwellings, with these dwellings accounting for approximately 29% of total UK energy consumption, contributing 14% of UK greenhouse emissions. As such, the UK government has identified the residential housing stock as one of the key opportunities for cost-effective, large scale carbon reduction.

The traditional building stock constitutes approximately 21% of these 29 million dwellings and, as such, the retrofit of the traditional buildings presents a sizeable opportunity and is becoming increasingly important as a means of reducing energy usage and combatting climate change.

With this opportunity comes an inherent risk due to the complex nature of traditional buildings, the nature of the heterogenous natural materials used in their construction, the conditions of the external environment, their occupants and, in undertaking retrofit, the alteration of a complex interrelationship of the physical properties of moisture, ventilation and heat, which – subject to the building being adequately maintained – will have achieved a natural equilibrium state to maintain the health of the building.

The alteration of the physical conditions of a traditional dwelling and the organically achieved balance of moisture, ventilation and heat has the potential to result in a number of unintended consequences in the form of moisture penetration, interstitial condensation, thermal bridging, overheating and impacts to indoor air quality, resulting in risk of fabric decay or occupant health.

Whilst advancements within the field of retrofit have been made, there remains a lack of a clear, sufficiently detailed, systemic approach to design out unintended consequences during the energy retrofit of traditional buildings. This thesis is resultantly focused upon this topic and the investigation of the feasibility of developing an analysis process for the fabric related energy enhancement of 'typical domestic retrofit' to adequately design out unintended consequences.

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## (ii) Table of Figures

## (iii) Acronyms

| | |
|---|---|
| **AECB** | Association for Environment Conscious Building |
| **ARB** | Architects Registration Board |
| **BEIS** | Department for Business, Energy and Industrial Strategy |
| **BERR** | Department for Business, Enterprise and Regulatory Reform *(Disbanded 2009)* |
| **BRE** | Building Research Establishment |
| **BSI** | British Standards Institute |
| **CCC** | Committee on Climate Change |
| **CIAT** | Chartered Institute of Architectural Technologists |
| **CIBSE** | Chartered Institution of Building Services Engineers |
| **CIOB** | Chartered Institute of Building |
| **DECC** | Department of Energy and Climate Change |
| **DEFRA** | Department for Environment, Food & Rural Affairs |
| **ECO** | Energy Company Obligation |
| **EEM** | Energy Efficiency Measure |
| **EPC** | Energy Performance Certificate |
| **EWI** | External Wall Insulation |
| **IAQ** | Indoor Air Quality |
| **IWI** | Internal Wall Insulation |
| **LZC** | Low or Zero Carbon |
| **MEES** | Minimum Energy Efficiency Standards |
| **PAS** | Publicly Available Specification |
| **PHPP** | Passivhaus Planning Package |
| **POE** | Post Occupancy Evaluation |
| **RIAS** | Royal Incorporation of Architects in Scotland |
| **RIBA** | Royal Institute of British Architects |
| **RICS** | Royal Institution of Chartered Surveyors |
| **RH** | Relative Humidity |
| **SAP** | Standard Assessment Produce |
| **STBA** | Sustainable Traditional Buildings Alliance |
| **SWI** | Solid Wall Insulation |
| **RDSAP** | Reduced Data Standard Assessment Procedure |
| **VCL** | Vapour Control Layer |
| **VIPs** | Vacuum Insulated Panels |
| **VOCs** | Volatile Organic Compounds |
| **WUFI** | Wärme Und Feuchte Instationär |

We as an industry should not be afraid of energy retrofitting older, traditional or indeed historic buildings, but we need an agreed methodology and set criteria for assessment and implementation of measures and we need, as a matter of urgency, an education and accreditation system for professionals in the energy retrofit industry

Peter Cox 2017

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## 1.0 Introduction and Context

During the development of this thesis, the British Standards Institution published a new Publicly Available Specification: PAS 2035:2019 – *Retrofitting dwellings for improved energy efficiency – Specification and guidance*.

This document has numerous synergies with the predominant focus of this thesis.

### 1.1 Introduction

Evidence in support of global warming induced climate change is clear, with increases in concentrations of "greenhouse gases", artic sea ice decline, global sea-level rise and global surface temperatures increases (IPCC 2001), presenting a global existential threat to humanity.

The United Kingdom has an estimated 29 million existing dwellings (CCC 2019a), with these dwellings accounting for approximately 29% of total UK energy consumption, contributing 14% of UK greenhouse emissions (CCC 2018). Given the scale of emissions from the built environment, the UK government has identified the residential housing stock as one of the key opportunities for cost-effective, large scale carbon reduction (DECC 2012).

Traditional buildings, that is buildings constructed prior to 1919 and typically of solid wall or solid timber frame construction (STBA 2015), account for roughly 21% of the UK's existing domestic housing stock (MHCLG 2019). As a result, the retrofitting of traditional homes with energy improvement measures presents a sizeable opportunity, although with this opportunity comes an inherent risk.

Traditional buildings are fundamentally distinct to modern buildings in their use of materials, construction, detailing and underlying philosophy. Traditional buildings are constructed to accommodate fluctuations in their environment with, for example, vapour open materials permitting an element of moisture to penetrate the structure and naturally evaporate. Traditional buildings therefore require particular consideration with respect to moisture, heat and ventilation.

Whilst the conservation sector – which is focused upon traditionally constructed buildings – is maturing and, driven by academic research and a number of bodies including: the Sustainable Traditional Buildings Alliance (STBA), the Association for Environment Conscious Building (AECB), Historic England and Historic Scotland, the understanding of the interplay of fabric, moisture, ventilation and heat has increased – and despite an appreciation of the dangers of a one-size-fits-all approach – there remains a gap in outlining a broadly agreeable, objective process to sufficiently analyse a building so as to identify suitable methods of intervention as a part of an analytical design process and be clearly aware of the result and implications – or "unintended consequences" – following their implementation.

This existing lack of a process, standard or accreditation for domestic retrofit, coupled with increased Government policies, financial subsidies and incentives leading to businesses to offer, possibly unscrupulous, retrofit services and driving individuals to retrofit their homes, results in an increased risk of improper, ill-conceived intervention measures. As highlighted by Traynor (2019), the construction industry does not provide an affordable bespoke solution to meet the variable conditions of the existing building stock for retrofit and there is a tendency to regard retrofit as simply another opportunity to 'sell a product', such as external wall insulation, windows or ventilation systems, without considering the potentially adverse impact of limited measures.

The lack of a sufficiently detailed, integrated whole house analysis approach, considering: context, fabric, moisture, ventilation and heating, may possibly lead to unintended consequences such as interstitial condensation, damp, mould growth and poor indoor air quality being introduced as a by-product of the retrofit process.

These unintended consequences lead to the detriment of both the building, by way of its historic fabric, and the occupants with financial and emotional stress and possible health implications. The sufficient understanding of a building prior to retrofit is therefore paramount.

## 1.2 The Problem: The Analysis Gap

Retrofit consists of a broadly sequential, albeit often iterative, process, as highlighted within Figure 1.1, incorporating an initial assessment or analysis of a structure, which in-turn informs the design of a, or a series of, retrofit intervention measures, leading to an installation of those measures with the upgraded building to be used by the occupants.

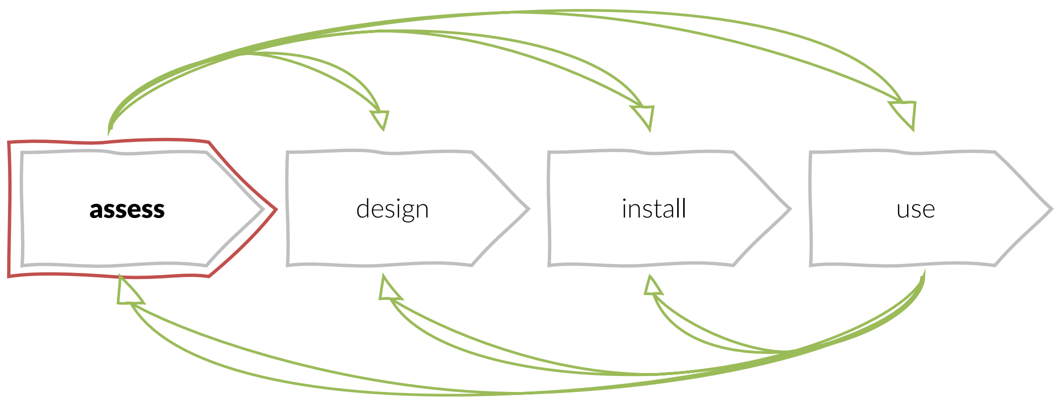


**Figure 1.1** – Retrofit Process (Author's own 2019, based on STBA 2015)

The process can equally be extended, or more explicitly detailed, to ensure a detailed brief is received from the client at the outset of the project and that following use, some form of Post-Occupancy Evaluation (POE) or on-going monitoring is completed to iteratively feedback learnings and outcomes from the retrofit that would substantiate design decisions and enhance decision making for future projects.

Each of the phases are critical in their own regard to the overall success of a retrofit, although the assessment phase at the outset underlies the whole process, ensuring the subsequent phases are adequately informed.

The assessment phase consists of a combination of desk-based and field-based research to gather sufficient information regarding the target building, its context, inhabitants and the desired outcomes to outline appropriate and sympathetic design solutions whilst identifying corresponding risk, or concerns which could lead to unintended consequences.

In completing an assessment of a building undergoing retrofit, and as per Figure 1.2, the STBA identifies three broad categories of concern or risk: technical, heritage and energy (STBA 2018).

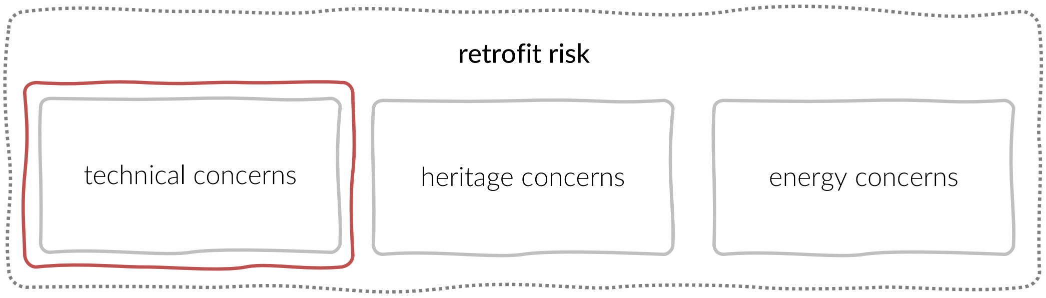


**Figure 1.2 –** Retrofit Risk Categorisation (Author's own 2019, based on STBA 2018)

Technical concerns highlight those technical aspects, primarily focused on building physics and an alteration of heat, moisture and ventilation within the building leading to risks such as the introduction of accumulated moisture or poor air quality. Heritage concerns are related to risks associated with loss of historic fabric and the significance of the structure. Energy concerns consider factors such as installation quality of the retrofit and the rebound effect (whereby the full energy saving of a measure is not achieved as the retrofit alters occupant behaviour to compensate for the saving).

In addition to an appreciation of risk, a holistic assessment process must consider equally critical factors such as cultural significance, including evidential, historical, aesthetic and communal value; conservation principles such as minimal intervention, authenticity, appropriateness, reversibility and workmanship (English Heritage 2008); and underlying practicalities, including factors such as the disturbance of a retrofit measure or the loss of internal floor space associated with IWI – this is all equally in isolation of factors such as up-front capital cost, whole life-cycle cost and embodied carbon.

The successful retrofit of buildings is complex with, as recognised by King (2016), traditional buildings being the most challenging to improve from a thermal performance perspective as, due to their use of natural materials and porous construction, they are the most susceptible to the effects of moisture ingress, and the altering of moisture, ventilation and heat within the building, thereby requiring accurate assessment and greater control when selecting a form of enhancement. This is further echoed by Smith (2017), in highlighting that the most acute problems involved with energy retrofit occur when the condition of the building is inadequately assessed prior to insulating, only resultantly serving to worsen any existing issues.

Despite this necessity for accurate assessment of traditional buildings undergoing retrofit, as identified by the STBA in their 2012 report, Responsible Retrofit of Traditional Buildings (STBA 2012), the lack of a clear systemic approach regarding assessment and retrofit of traditional buildings exists and is required if unintended consequences are to be avoided.

Whilst advancements in the industry have been made in the intervening period since the STBA's report – some of which have materialised over the course of developing this thesis – there remains an often vague reference of the need to "complete an assessment of the structure". For example, TM60: Good practice in the design of homes, the leading good practice design guide for the Chartered Institution of Building Service Engineers states: "detailed building surveys should be undertaken to gather key information including details of the existing building fabric and services and occupant requirements" (CIBSE 2018, p. 17). Even BSI's own leading conservation document, BS 7913 – Guide to the conservation of historic buildings, indicates when alterations are implemented to a structure: "an analysis on this should be carried out" and "this could include comparing current environmental with predicted environmental conditions" (British Standards Institution 2013, p. 11).

It is appreciated that the aim of these documents is not restricted to outlining an analysis framework and it is unreasonable to expect them to do so given the vastness of the subject area, although there remains a lack of a reference to any form of objective, systematic process for the adequate assessment of retrofit.

The development of Responsible Retrofit Guidance Wheel (STBA 2018a), has gone some way to address the paucity of adequate retrofit assessment guidance, being launched in an effort to aid decision making and a way of learning about traditional building retrofit. However, whilst the guidance wheel is useful in identifying relevant areas of consideration for a particular intervention, it lacks the simplicity of a linear process, with the sheer level of detail and volume of referenced guidance overwhelming – the tool cites 46 relevant pieces of research and guidance for wall insulation alone.

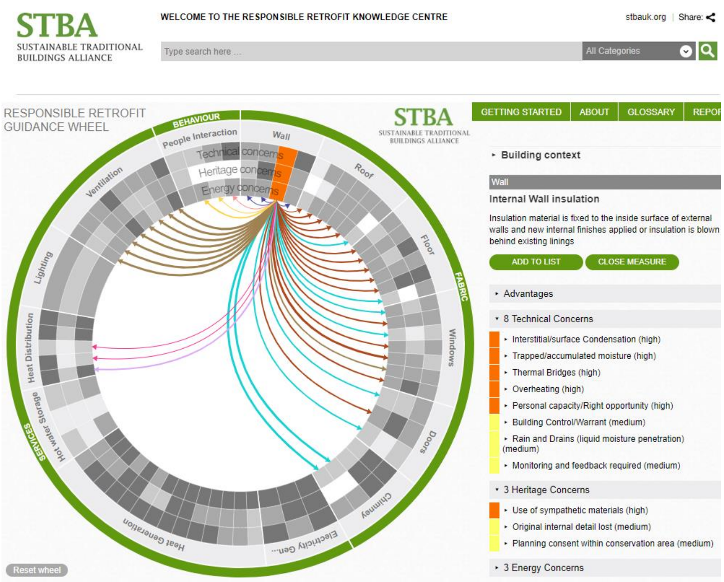


**Figure 1.3 –** STBA Responsible Retrofit Guidance Wheel (STBA 2018a)

This lack of a reference to a detailed process equally abstracts from the sheer range and plethora of additional analysis tools, techniques and software and, whilst there have been a number of high-profile retrofit case studies, such as the retrofit of the Grade I listed New Court at Trinity College in Cambridge (Taylor 2017), which included a detailed three-year period of assessment including detailed sampling and modelling of the building, and despite an appreciation of the dangers of a one-size-fits-all approach, there remains a gap in outlining a broadly agreeable, sufficiently detailed objective systemic whole house analysis framework and process for the retrofit of small-scale domestic traditional buildings, so as to be to clearly aware of and design out unintended consequences.

This thesis is resultantly focused upon this topic and the investigation of the feasibility of developing an analysis process for the fabric related energy enhancement of 'typical domestic retrofit', including what this analysis would consist of, what tools, techniques and level of monitoring – and over what time period – is required and feasible to adequately design out unintended consequences.

## 1.3 Policy Context

### 1.3.1 UK Energy Policy

The pace of global industrial, economical, technological and sociological growth has exponentially increased in the past centuries, with the increasingly readily and affordable access to energy a primary driver (Rudel and Hooper 2005). Advancement ultimately comes at a cost, with an increased use in energy, principally in the form of burning fossil fuels, resulting in increased production of 'greenhouse gases', such as Carbon Dioxide ($CO_2$), leading to global warming and climate change. Evidence for global warming induced climate change in the UK and globally – whilst still paradoxically subject to debate – is clear, with increases in concentrations of various greenhouse gases in the Earth's atmosphere, Artic sea ice decline, global sea-level rise and global surface temperatures having risen by 0.6°C, with those over central England rising by 1°C since the late 19th century (IPCC 2001; Hulme et al. 2002; CCC 2018).

The global existential threat of global warming has resulted in a raft of increasingly restrictive policy and legislation, originating with the global adoption of the United Nations Framework Convention on Climate Change in 1992, extended shortly thereafter by the Kyoto Protocol – a UN international treaty adopted in 1997 and entered into force in 2005. The Kyoto Protocol committed, for the first time, parties to reduce greenhouse gas emissions, with the UK exceeding its underlying obligation and committing to reduce greenhouse gas emissions by 12.5% by 2010, relative to 1990 levels (DECC 2015).

These targets have continued to evolve as global scientific and public scrutiny, coupled with the establishment of numerous independent statutory bodies, such as the Committee on Climate Change, lobby governments for more aggressive target reductions. A more ambitious target of a 60% reduction by 2050, again relative to 1990 levels, originally suggested by the Royal Commission on Environmental Pollution (RCEP), was adopted by the Government in the 2003 Energy White Paper (DTI 2003). This 60% reduction target has twice since been enhanced. The Climate Change Act 2008 established a target for the UK to reduce carbon emissions by at least 80% by 2050, relative to 1990 levels, with a series of legislated 'carbon budgets' which set legally binding targets for emissions reductions between 2008 and 2032 in order to ensure a trajectory towards the 2050 target. In 2019, following advice from the CCC (CCC 2019b), the UK Government revised this target, legislating and committing the UK to reduce its greenhouse gas emissions to net-zero by 2050 (HM Government 2019).

### 1.3.2 Domestic Residential Building Energy Policy

As highlighted by the CCC (2019a) the UK will fail to meet targets for emissions reduction without near complete decarbonisation of the housing stock (CCC 2019a).

Dwellings account for approximately 29% of UK total energy consumption (BEIS 2019a), contributing 14% of UK greenhouse emissions (CCC 2018) therefore, whilst generic industry wide climate change policy and legislation has evolved, industry specific building policy has equally been required to evolve to contribute to the carbon reduction targets.

Whilst policy has predominantly focused on new build, the UK has an estimated 29 million existing dwellings (CCC 2019a) and the oldest housing stock of EU member states (Nicol et al. 2016). Dwellings have long physical lifespans, with a low turnover of stock, estimated to be in the region of 1% (Ravetz 2008) and as result, 75% of this existing stock is forecast to still exist in 2050 (Wright 2008). Given the proportion of the existing stock forecast to exist in the future, coupled with the poor quality of the building fabric across the whole stock meaning that space heating accounts for roughly 60% of total delivered residential energy demand (Environmental Change Institute 2005), there has been an increasing emphasis and driver on energy efficiency and retrofit.

The UK Government has identified the residential housing stock as being one of the key opportunities for cost-effective, large scale carbon reduction (DECC 2012) and has introduced a series of successive policies and documentation including the Code for Sustainable Homes, the Energy Company Obligation (ECO), the Minimum Energy Efficiency Standards (MEES), in amongst progressive modifications to Building Regulations (Approved Document Part L) with a mixture of mandatory, advised and incentivised energy targets.

Retrofit is seen as not only a necessity in terms of carbon reduction, although is equally complimented by drivers such as fuel poverty, with the BEIS (2019b) identifying an estimated 10.9% (approximately 2.53 million households) of households in England being in fuel poverty in 2017.

## 1.4 UK Domestic Housing Stock

As commented by King (2016), given the environmental impact of the legacy building stock, the option to do nothing is not viable in global terms and therefore retrofit of the traditional building stock is not only required, although inevitable.

As a result of the increasing drivers to retrofit the existing housing stock and the inevitability, this presents a sizeable opportunity, although equally inherently therefore a sizeable risk. In attempting to quantify the scale of this opportunity, or risk, in the context of the retrofit of traditional buildings, as per Figures 1.3, approximately 21% (*c.* 5m homes) of the English housing stock are considered to be traditional (pre-1919).

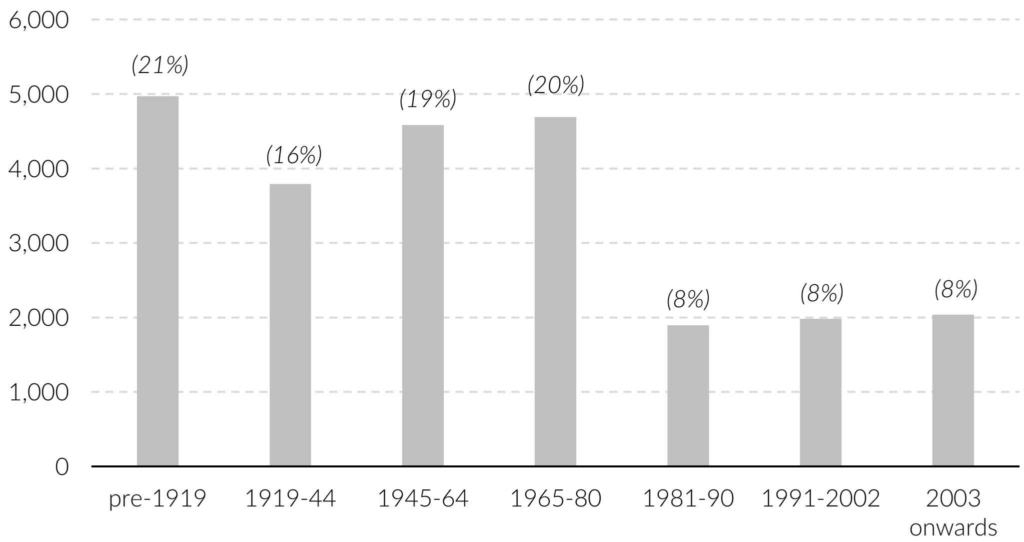


**Figure 1.4 –** English Housing Stock by Dwelling Age (000s) (MHCLG 2019)

The Government has equally set out a high level of ambition with regards to energy efficiency and outlined, within the Clean Growth Strategy published in 2018, a target to ensure all fuel poor UK homes to be upgraded to Energy Performance Certificate (EPC) – an EPC being a broad approximation of the energy costs for a building – band C by 2030, with an aspiration for as many homes as possible to be EPC band C by 2035 where practical cost-effective and affordable (HM Government 2018).

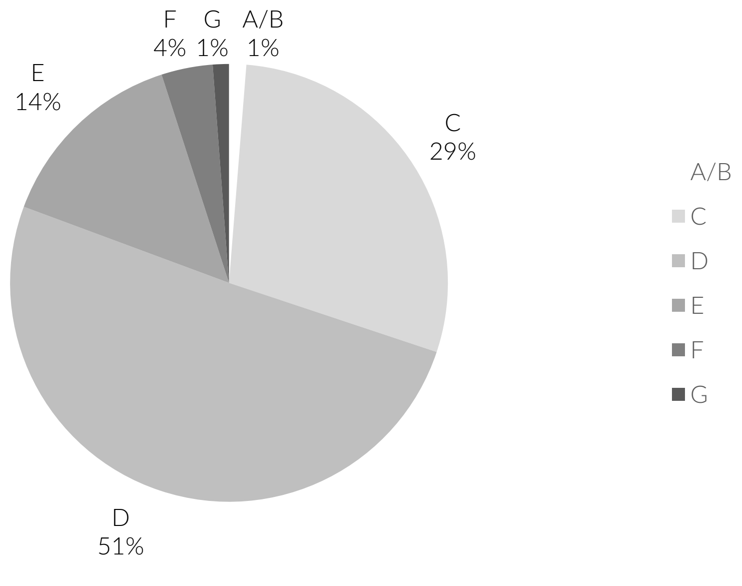


**Figure 1.5 –** English Housing Stock by EPC Band (MHCLG 2019)

Whilst data is not available to determine the extent of the traditional building stock that falls into particular EPC bands, logic would dictate that, given the crudities of the EPC (RdSAP) assessment process and assumptions, and given the form of construction and materials, the majority of traditional homes fall into the D, E, F and G bands – which are increasingly deemed to be the worst performing and energy efficient homes.  This again presents a sizeable risk for those traditional buildings not adhering to the Governments EPC targets, with the potential fast-tracking of retrofit of these properties by insufficiently informed schemes leading to unintended consequences.

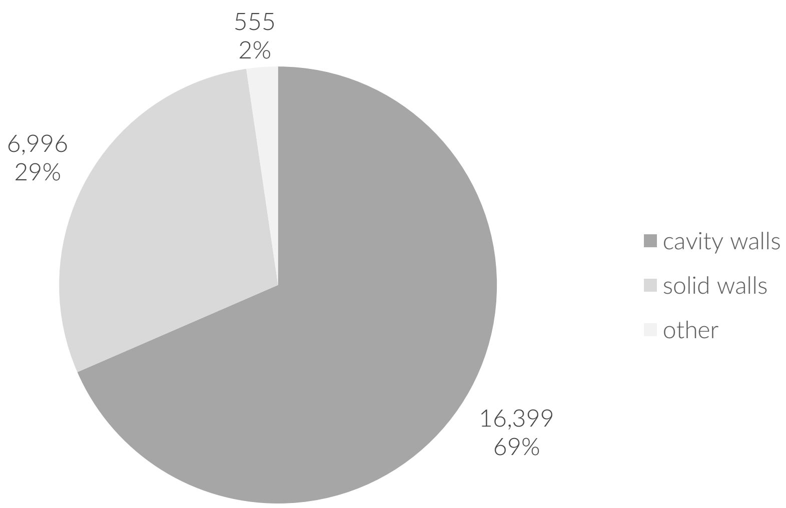


**Figure 1.6 –** English Housing Stock by Main Wall Type (MHCLG 2019)

## 2.0 Retrofit

### 2.1 What is Retrofit?

Retrofit is the process of improving the energy and environmental performance of buildings through an individual or combination of measures highlighted within Figure 2.1 and broadly categorised between three key areas: fabric, services and people (STBA 2015).

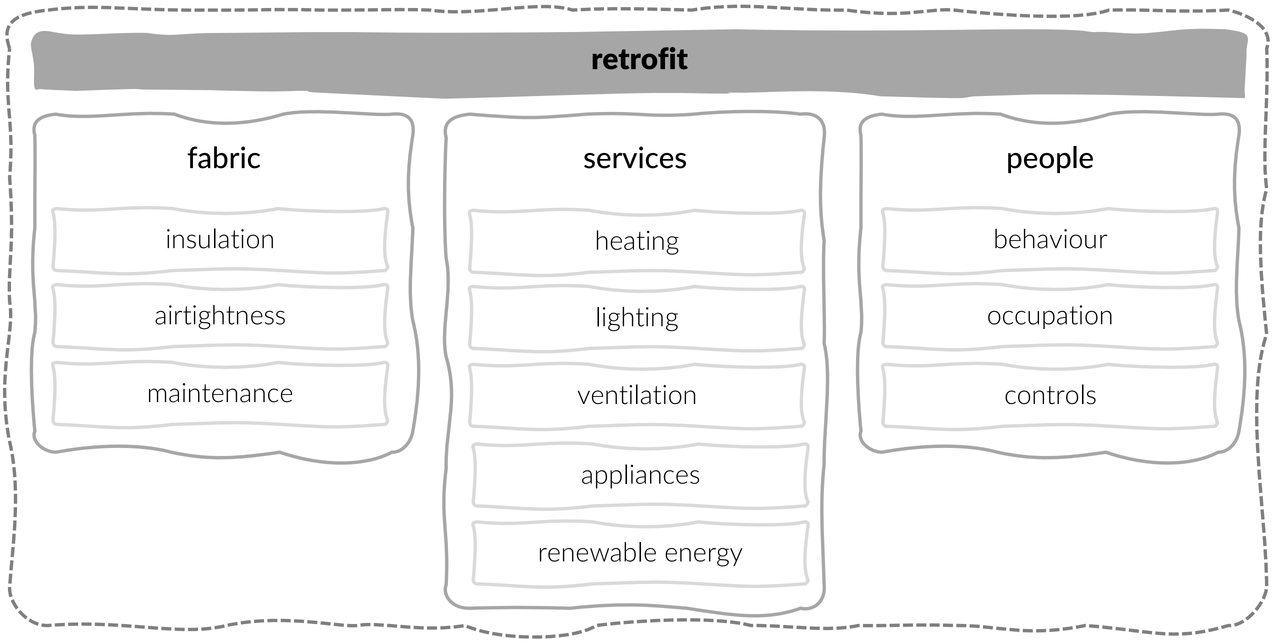


**Figure 2.1 –** Retrofit upgrade measures: fabric; services; people (Author's own 2019, based on STBA 2015)

Whilst measures are often deemed to be physical in nature, such as the installation of insulation (a fabric-related intervention) or upgrading a heating and lighting installation (a service-related intervention), a more integrated approach to retrofit equally considers the role and contribution of people and the combination of all of the factors as a whole.

### 2.2 Why Retrofit

There are a wide range of drivers for retrofit, as per Figure 2.2, ranging from lowering fuel bills, improving the comfort of a home, concern for the environment or as a mandatory requirement to ensure legal compliance. Any one or combination of these may prompt the decision for retrofit.

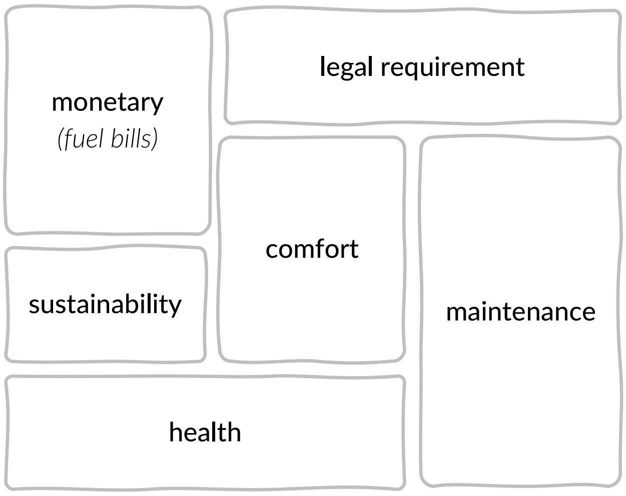


**Figure 2.2** – Why Retrofit? (Author's own 2019)

## 2.3 Deep Retrofit, Whole House & Responsible Retrofit

There is no broadly recognised and accepted definition of "deep retrofit", although it can be deemed to consist of an integrated whole house approach considering a building as a series of interrelated systems encompassing: insulation, airtightness, ventilation, fabric, building context, building services and occupants, to devise a holistic strategy and set of retrofit measures to transform the performance of a building in terms of both energy and comfort. An approach may include, for example, the provision or enhancement of wall, floor and roof insulation, new doors and windows, enhancing airtightness and service upgrades.

It is important to note, as highlighted by PAS 2030 (British Standards Institution 2019a), retrofits can be both one-off installations of improvement measures, or a staged approach, whereby a series of measures are introduced over a period of time in a cohesive strategy although, crucially, irrespective of the implementation, it is fundamental to ensure a cohesive understanding of any structure and those interrelated elements prior to any intervention.

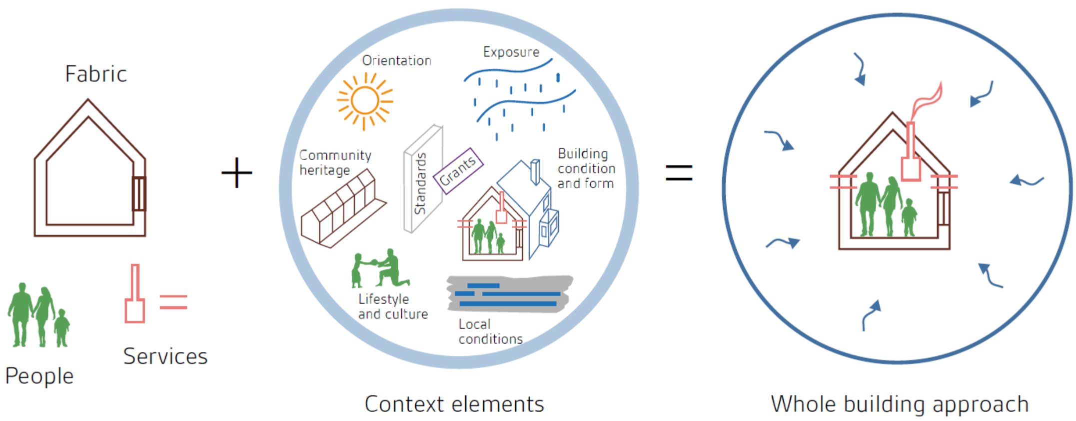


**Figure 2.3 –** The whole house approach (May and Sanders 2018)

This approach differs from a less scientifically considered and *ad hoc* "narrow retrofit" approach whereby an individual or minimal range of measures may be installed in isolation of each other, without a broader consideration of the long-term strategy for the building, or crucially, the potential unintended consequences of the installation of measures in isolation. As highlighted by Traynor (2019), while the application of piecemeal, unplanned retrofit measures can cause significant problems in any building, the impact on traditional buildings can be much more severe.

A whole house, deep retrofit, approach has been championed by several organisations including the AECB, the National Energy Foundation, the Passivhaus Trust, Retrofit Academy, and the STBA, with the concept supported by the Government following the Hansford and Bonfield (Each Home Counts) Review (STBA 2016). The whole house concept was introduced in direct response to the introduction of unintended consequences following retrofit of traditional buildings, including fabric decay, moulds and condensation, failure to meet reduction targets and poor indoor air quality (Corbey and Loxton 2017).

The STBA's 2012 report, Responsible Retrofit of Traditional Buildings, commissioned by the DECC, equally identified that problems experienced following retrofit were predominantly not as a result of individual building elements, although rather either at the interfaces between elements, technologies or building processes; or, through interactions between buildings, measures and people (STBA 2012). These findings spawned the concept of "Responsible Retrofit", that although semantically different, is aligned with the integrated, holistic principles of whole house and deep retrofit.

## 2.4 Traditional, Modern & Hybrid Buildings

In undertaking an assessment of a traditional building, it is fundamental to initially appreciate the properties of the building and how these differ to modern forms of construction. In gaining an understanding of a traditional building, it is equally necessary to appreciate the complexities associated with how the building may have evolved over the passage of time via past retrofit or alteration, often with inappropriate modern materials such as a hard cementitious mortar or synthetic waterproofing treatments, to form a 'hybrid' building that may consist of a range of materials and forms of construction (Bristol City Council 2015).

Traditional buildings, whilst varying with period of construction, are typically constructed from local vernacular materials, primarily due to the economics and logistical restrictions in transporting materials and skilled labour over longer distances evident at the time. These traditional materials are equally permeable in nature, being commonly of stone, brick, timber and lime, with the vapour open materials permitting the passage of water vapour and air through the structure.

Due to construction methods, technologies and detailing, traditional buildings were equally exposed to more natural ventilation, with limited materials intended specifically for the purposes of insulation. As a result of the physical properties – and whilst dependent upon their condition – traditional buildings tended to heat up and cool down more slowly than modern homes, with thick and dense materials such as brick and stone offering thermal mass permitting these materials to act as a thermal store, taking on heat and releasing this slowly. Moisture is equally permitted to more readily enter and escape the structure via the nature of typical porous, vapour permeable, hygroscopic materials (that being materials that readily absorb vapour as relative humidity increases and release it as humidity drops); gaps in fabric and at interfaces; low density draughty windows, doors; and chimneys.

Fundamentally, traditional properties were more required to rely on – and be impacted by – their context and orientation for light and heat from the sun, and from the wind to assist in adequately ventilating and drying out the vapour open structure (Pender et al 2014).

This approach and philosophy profoundly differs to modern construction, which is increasingly focused on hermetically sealing the structure with, commonly, non-permeable, hydrophobic materials, with more focus placed upon insulation and – to an extent – airtightness. Increased insulation and airtightness results in modern structures warming up quicker, with the insulation and airtightness limiting this heat from escaping and therefore raising internal air temperature. Moisture is equally predominantly prevented from entering the structure in the first instance, with any internal moisture ideally controlled and extracted via a number of means, with vapour control layers installed to prevent moisture seeping into the building fabric.

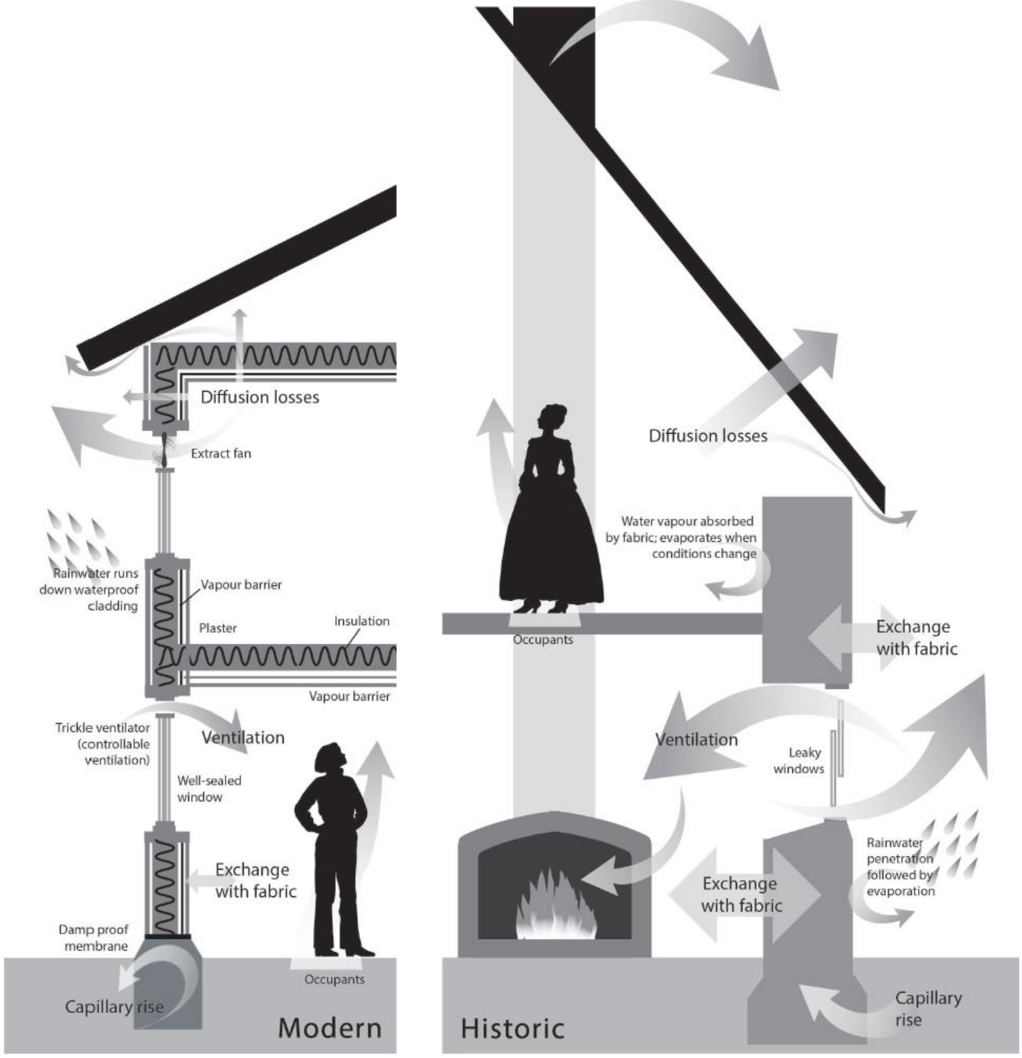


**Figure 2.4 –** Typical differences in the movement of moisture for a historic building and a modern building (Pickles and McCaig 2017)

Given traditional buildings and their materials more readily taking on and being impacted by moisture, heat and ventilation, traditional buildings are typically more complex in nature than that of modern buildings and require more detailed consideration and appreciation of building physics during retrofit (Pickles and McCaig 2017).

## 2.5 Building Physics

### 2.5.1 A Perfect Balance: The Interrelation of Moisture, Ventilation and Heat/Air Temperature

As we have seen with traditional buildings, their fundamental construction is such that the building permits an element of natural fluctuation in three key principle variables: moisture, heat and ventilation. The interrelation of these three elements, coupled with a buildings underlying good condition and regular maintenance ensures this system stays in balance.

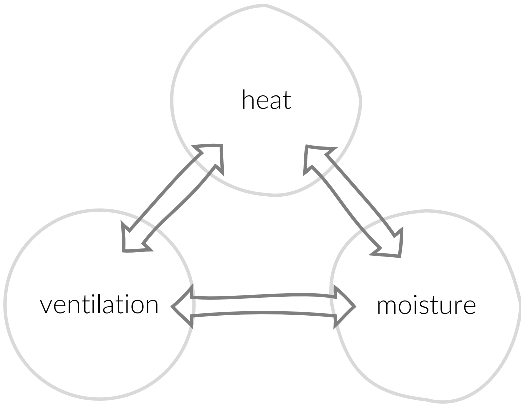


**Figure 2.5 –** The interrelationship of moisture, ventilation and heat (Author's own 2019)

As highlighted by Historic Scotland (2013), the consideration of moisture movement and ventilation is of fundamental importance when dealing with many older buildings. Retrofit and introduction of technical interventions has the potential to impact one or any combination of these variables, resulting in an existing balance becoming compromised leading to potential implications – or unintended consequences – to the fabric, building and occupants.

As an example, when upgrading the windows to a building, airtightness will often be increased and space heating demand may be reduced due to increased thermal performance; however, heating of the property may be reduced and window reveals may become colder in relation to the windows. Now, due to cold window reveals, an increase in air temperature, permitting the air to hold a higher degree of moisture and leading to an increase in relative humidity, coupled with decreased ventilation, may lead to the window reveals being more susceptible to condensation, leading to mould and impacts to poor indoor air quality.

In order to adequately appreciate the implications resulting from energy related retrofit, it is first necessary to have a fundamental underlying appreciation of building physics and specifically those of heat, moisture and ventilation and how the lack of understanding in the altering of these agents and their interrelationships can result in unintended consequences,

## 2.5.2 Moisture

As highlighted by Smith (2017), the majority of issues stemming from energy retrofit of traditional buildings are related to moisture.

Traditional, solid masonry buildings function effectively as moisture reservoirs, with the ability to absorb and retain moisture during times of the year when the volume of moisture outweighs its evaporation and drying potential, principally autumn and winter, with this balance being restored during the warmer, dryer spring and summer seasons. As can be seen within Figure 2.6, buildings are exposed to a huge number of internal and external sources of both liquid water and water vapour.

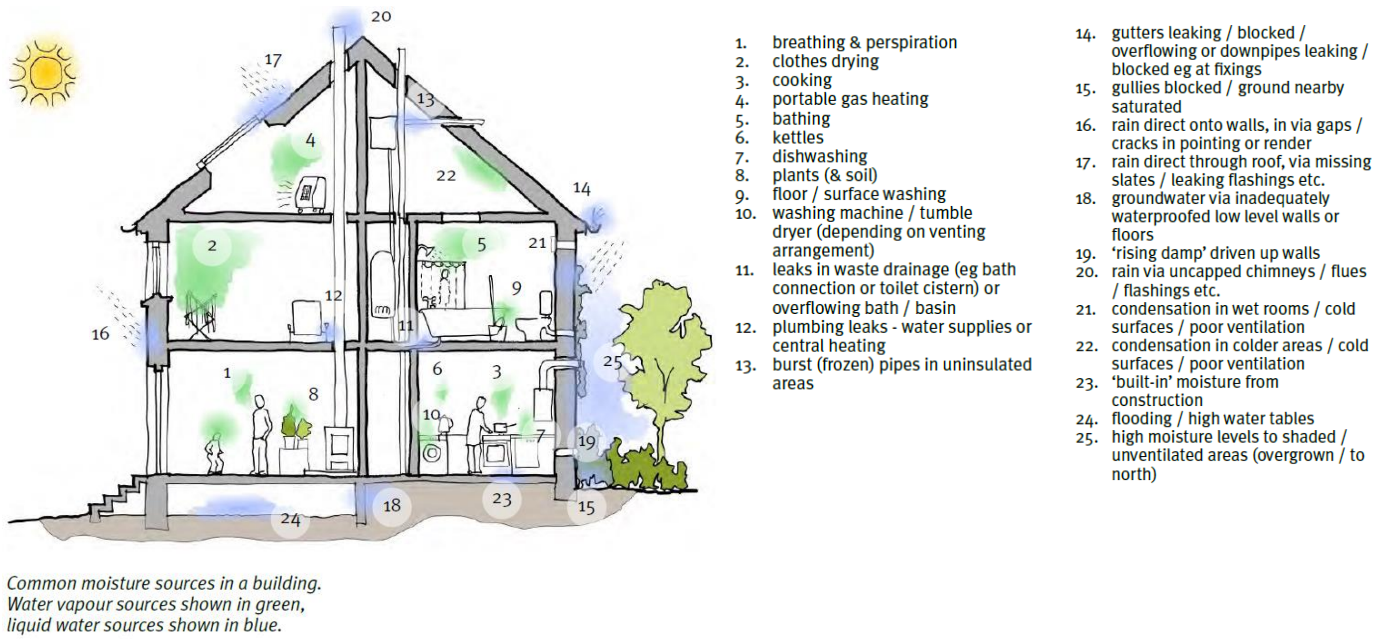


**Figure 2.6 –** Common moisture sources in a building (Morgan 2018)

Having a sound appreciation of the existing sources and extent of moisture evident within a property prior to retrofit is paramount as this moisture may be extant at time of intervention and therefore may become trapped or may progressively build-up over the passage of time leading to unintended consequences.

## 2.5.3 Ventilation

Ventilation is the term used to describe air movement which is designed, intentional and controllable, as opposed to infiltration which is the term used to describe non-intended, non-controllable air movement (Morgan 2018).

Ventilation is required within buildings in order to provide fresh air; maintain a healthy indoor environment; remove excess moisture and assist in controlling condensation; remove pollutants;

ensure the safe operation of particular combustion appliances; and, in warm weather, assist in cooling occupants.

In traditional buildings the main mechanisms to provide ventilation are openable windows, chimneys, fires – in addition to general air leakage (air-infiltration) – coupled with cross and stack ventilation.

The adequate ventilating of buildings in intrinsically linked with the concept of airtightness – a measurement of air permeability and the inherent gaps and leakage points apparent in a building. Air permeability is a measure of the volume of air ($m^3$), escaping per hour for each $m^2$ of external surface area, being referred to in a single metric as $m^3/hr/m^2$ at a standard pressure difference of 50 pascals.

The appreciation of the concept of ventilation and airtightness is paramount in retrofit as not only do draughts result in roughly 40% of heat loss in a typical building (Morgan 2018), although as we have seen, ventilation and infiltration assist in controlling the dynamic equilibrium of moisture within a traditional building by permitting adequate dissipation of moisture and providing fresh air. If energy related retrofits, whether intended or otherwise, increase airtightness without a concomitant consideration of the ventilation strategy, this can lead to poor air quality, damp and mould. As such, airtightness must be considered in association with ventilation during retrofit.

### 2.5.4 Heat

Heat as a physical property is crucial in the consideration of retrofit as not only does it directly impact thermal comfort although it is equally intrinsically linked with moisture and the concept of relative humidity (RH) to dictate the amount of water vapour the air can hold which can have dramatic implications should this be altered without first having a sound appreciation of the underlying physics.

Relative humidity is used to quantify the amount of water vapour in the air as a proportion of the total water vapour the air is able to carry at a given temperature without reaching saturation point. The amount of water vapour that air can hold is dependent upon its temperature and thus, as air temperature increases for a fixed proportion of water vapour, its RH decreases. Correspondingly, if air temperature is decreased, again with a fixed proportion of water vapour, its RH increases, with saturation point occurring at 100% RH.

The alteration of the thermal characteristics of a building during energy related retrofit, e.g. following the insertion of IWI, without due consideration to the impact of air temperature and heating, may well lead to numerous forms of unintended consequences in the form of condensation, damp, mould growth and fabric decay.

### 2.6 Unintended Consequences

As we have seen, the interactions between a building and its internal and external environments are complex and dynamic. It can therefore be difficult to sufficiently predict the effects of energy related retrofit measures and to assess the technical risks with any degree of certainty.

Negative outcomes as a result of the execution of an improper or ill-informed fabric related energy retrofit with a lack of sufficient, detailed analysis, taking an integrated whole house approach incorporating fabric, condition, moisture, ventilation and heating, are collectively termed "unintended consequences".

As per Figure 2.7, unintended consequences in the context of energy related retrofits are introduced when some form of fabric related energy retrofit measure targeting the enhancement of thermal insulation and, or, airtightness, results in an alteration of the physical properties of one or any combination of moisture, heat or ventilation within a building leading to unintended consequences in the form of thermal bridging, condensation and moisture penetration, which in-turn are physically manifested in any combination of fabric decay, damp and mould, overheating or poor indoor air quality.

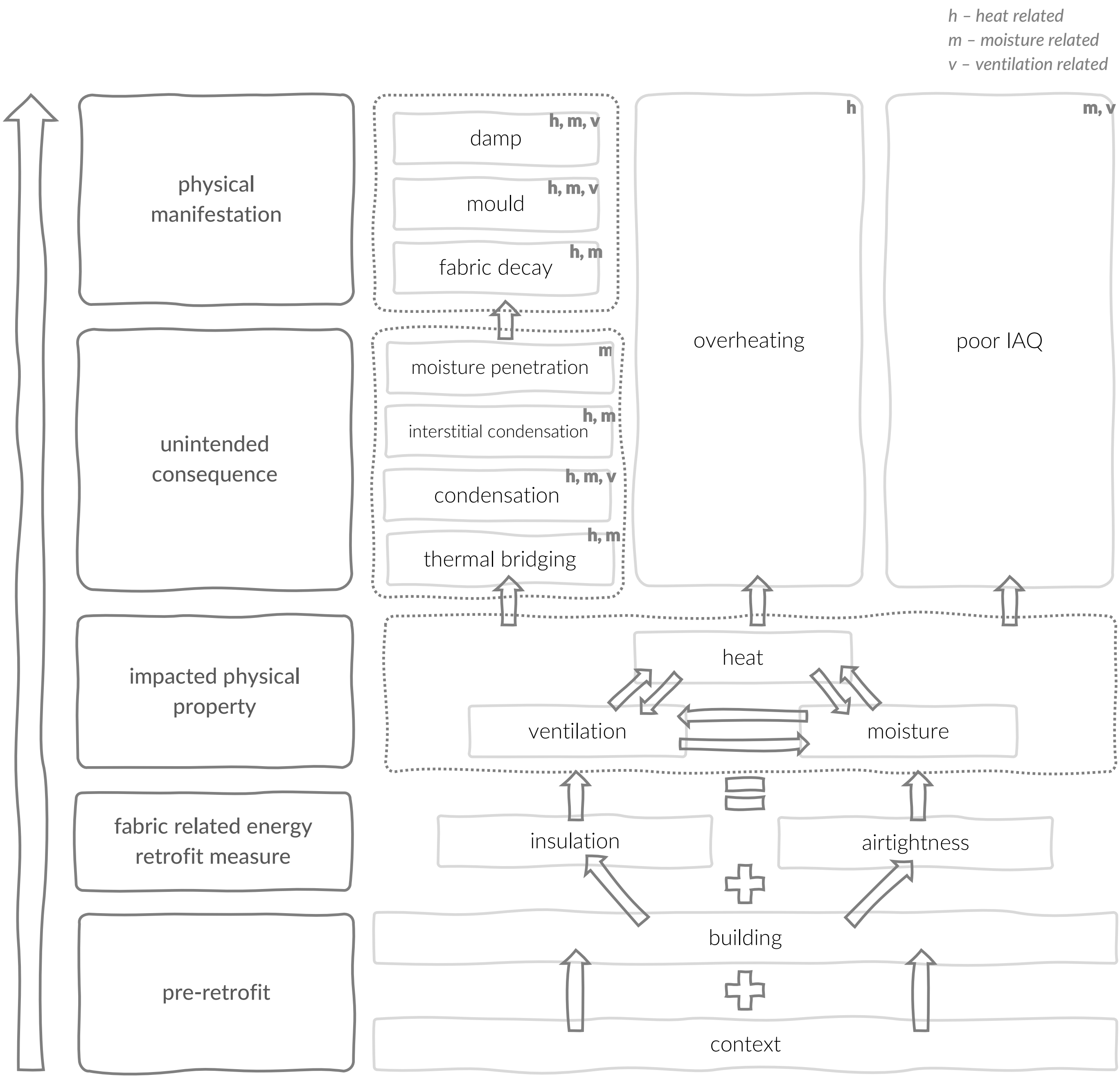


**Figure 2.7 –** Unintended consequences workflow (Author's own 2019)

Research completed by the BRE (King 2019) as a result of unintended consequences introduced following the installation of SWI, determined a list of the 19 most commonly experienced unintended consequences encountered – included within *Appendix A*. Whilst the unintended consequences identified by the report are attributed to SWI, these can equally be attributable to many forms of energy related retrofit.

Of the 19 unintended consequences identified, the final six are more superficial in nature and less related to the adaptation of the physical properties of a dwelling, the remaining 13 consequences are more broadly categorised as issues relating to: condensation, interstitial condensation, thermal bridging, moisture penetration, overheating and indoor air quality.

### 2.6.1 Interstitial Condensation

As highlighted by Historic England (2016), the most significant risk in altering the thermal performance of traditional buildings is the creation of interstitial condensation – condensation between layers of the building fabric.

In an unaltered state, any moisture taken on by an element of a traditional building, such as a floor or wall, with permeable internal and external materials and finishes, and with historic high levels of natural ventilation and infiltration, will have been permitted to evaporate naturally.

As shown in research (Künzel and Holm 2009), the application of a fabric related energy retrofit measures can lead to significant risks for solid wall buildings due to an alteration of the hygrothermal dynamics of the element and the overall building from a previous uninsulated state, impacting the moisture absorption, its correlating drying potential and a previously established equilibrium point which will have allowed a healthy internal balance to be maintained (May 2012; Historic England 2016; Smith 2017).

In considering an example of the application of IWI to a traditionally constructed solid masonry wall, the application of insulation significantly impacts and cools the surface temperature of the masonry. In this situation, as described by Smith (2017), the temperature gradient in the insulation can be steeper than the dewpoint gradient, so vapour diffusing or carried via infiltration of warm moist air will condense at the interface of insulation and cold masonry where temperature and dewpoint gradients intersect. In traditional solid wall construction, this interface is commonly where the most vulnerable structural elements, such as timber lintels and joist ends exist. Given the nature of the materials they can effectively as a wick, taking on the moisture, leading to rot, fabric decay and to structural failure at its most severe. Excessive amounts of vapour condensing may equally lead to damp and mould growth being experienced either at the interstitial interface, or on the internal face of the wall, resulting in further fabric decay and impacts to indoor air quality.

### 2.6.2 Thermal Bridging

Thermal bridges can occur at any junction between building elements, or where the building structure changes resulting in locally reduced internal surface temperature and increased heat loss at the bridging location (BRE 2006). Each individual thermal bridge has a psi (ψ) value measured in W/mK.

Thermal bridges fall into two categories: repeating thermal bridges, such as timber joists embedded in an external wall or mortar joints; and non-repeating thermal bridges, such as junctions between a ground wall and external wall.

Thermal bridging – often equally referred to as cold bridging given the inherent reduced temperature at bridging locations – commonly occurs in construction in problem areas, such as floor-wall-roof junctions, door and window reveals, complex windows (e.g. bay windows, stone mullions and cills) where the thermal conductivity of adjoining elements sufficiently varies or there is some element of discontinuity in the building or thermal envelope (Heath 2015). Research has shown that thermal bridging can be responsible for up to 30% of a dwelling's heat loss (Energy Saving Trust 2009).

Variations in surface temperatures resulting from thermal bridges can result in the temperature gradient of air reaching a thermal bridge to rapidly decline below its dewpoint gradient leading to condensation and mould growth. Thermal bridges can equally lead to internal discomfort to occupants due to the fluctuations in localised temperature profiles resulting in a surface feeling or "giving off" a particularly cold sensation. A common typical example of a fabric related energy retrofit would be the application of IWI and a corresponding increase in airtightness, without the necessary equal application of insulation to the reveals surrounding a window. This would result in warm moist air, coupled with the decrease in ventilation, condensing on the cold surface of the reveals and leading to mould growth, equally impacting indoor air quality.

### 2.6.3 Moisture Penetration

Penetration of moisture following installation of fabric related energy retrofit may occur due to a number of reasons although is principally likely to occur due to a pre-existing defect in the fabric of the structure being inadequately rectified prior to retrofit.

A pre-existing defect, such as cracks or gaps in masonry pointing which, prior to retrofit, may have harmlessly dissipated due to adequate ventilation and heating of the structure may, post-retrofit, due to the entrapment of moisture and an alteration of the hygrothermal properties of the structure, result in this moisture penetrating the internal fabric of the structure resulting in damp and mouldy conditions which may equally impact indoor air quality.

### 2.6.4 Overheating

Overheating in buildings is the phenomenon of a person experiencing excessive or prolonged high temperatures within their home, resulting from internal and/or external heating gains, which lead to adverse effects on their comfort, health or productivity (Zero Carbon Hub 2008).

Historically, heat has been lost organically in uncontrolled ways from traditional buildings due to the absence or lower levels of insulation and natural infiltration through gaps or apertures within the building fabric. However, the ongoing drive for energy efficient, airtight buildings, coupled with an increase in more frequent and intense heatwaves and average temperature rises as a result of climate change, present growing evidence of homes being at increasing risk from overheating (Good Homes Alliance 2019a). As a result – and further exacerbated by an aging population whom are more susceptible to heat related illnesses and death (Zero Carbon Hub 2015) – this mandates the need for increasingly greater care and consideration of the potential for overheating during retrofit.

Overheating can have dramatic implications for occupants; during the summer heatwave in Northern France in August 2003, unprecedentedly high temperatures for a period of three weeks resulted in 15,000 excess deaths. The vast majority of these were among older people. Research after the heatwave event revealed that at least 50% of these deaths could have occurred due to exposure to heat in people's homes (Fouillet et al 2006)

It is equally important to consider an element of winter solar thermal gain can positively contribute to the sustainable heating of a dwelling although, as outlined by Jamieson (2019), positioning, altitude, exposure, site location and perimeter influences, such as other buildings and trees, are not seemingly embodied in the process of design within the context of overheating leading to a lack of consideration of occupant thermal comfort.

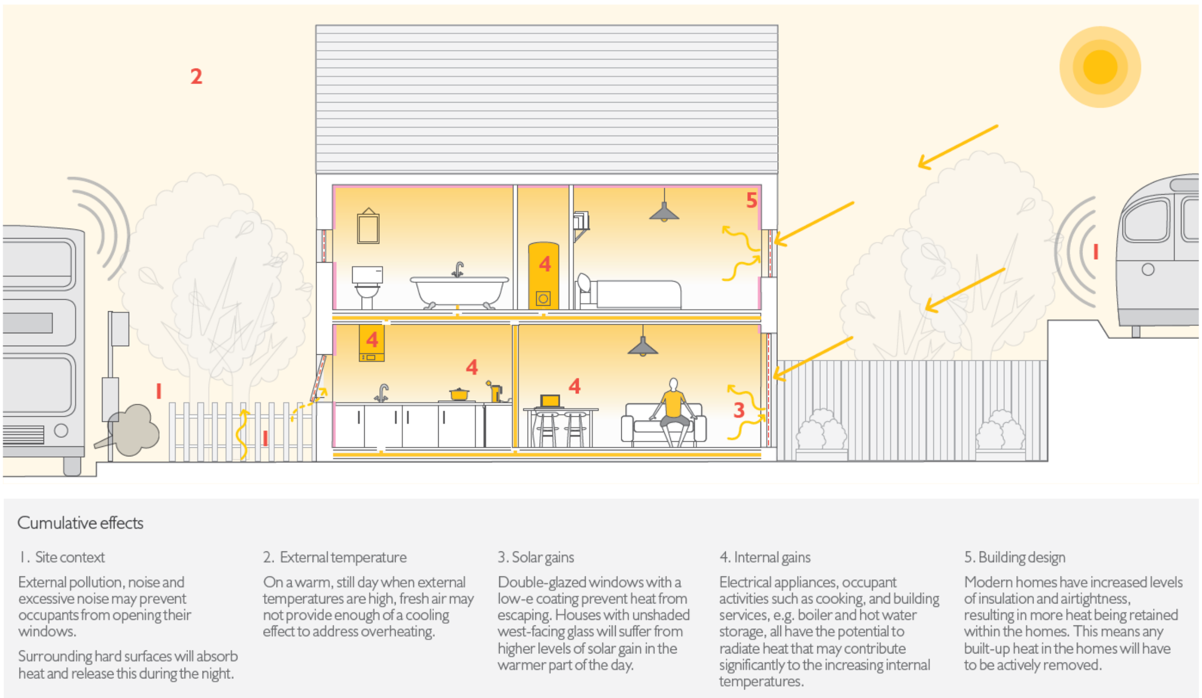


**Figure 2.8 –** Cumulative effects of overheating in homes (NHBC Foundation 2012)

Whilst ventilation and moisture are equally relevant considerations, heat and overheating is inextricably linked with the concept of thermal comfort. The Health and Safety Executive ([no date]) have outlined six basic factors – determined from Fanger Comfort Analysis – which combine to derive an indicator of thermal comfort – four environmental factors: air temperature, radiant temperature, air velocity and humidity; and, two personal factors: clothing insulation and metabolic heat – see Figure 2.9. Consideration of all of these is necessary to some extent in order to gain an appreciation of thermal comfort, whilst consideration of some or all of these factors in isolation will fail to yield a valid representation of thermal comfort or stress.

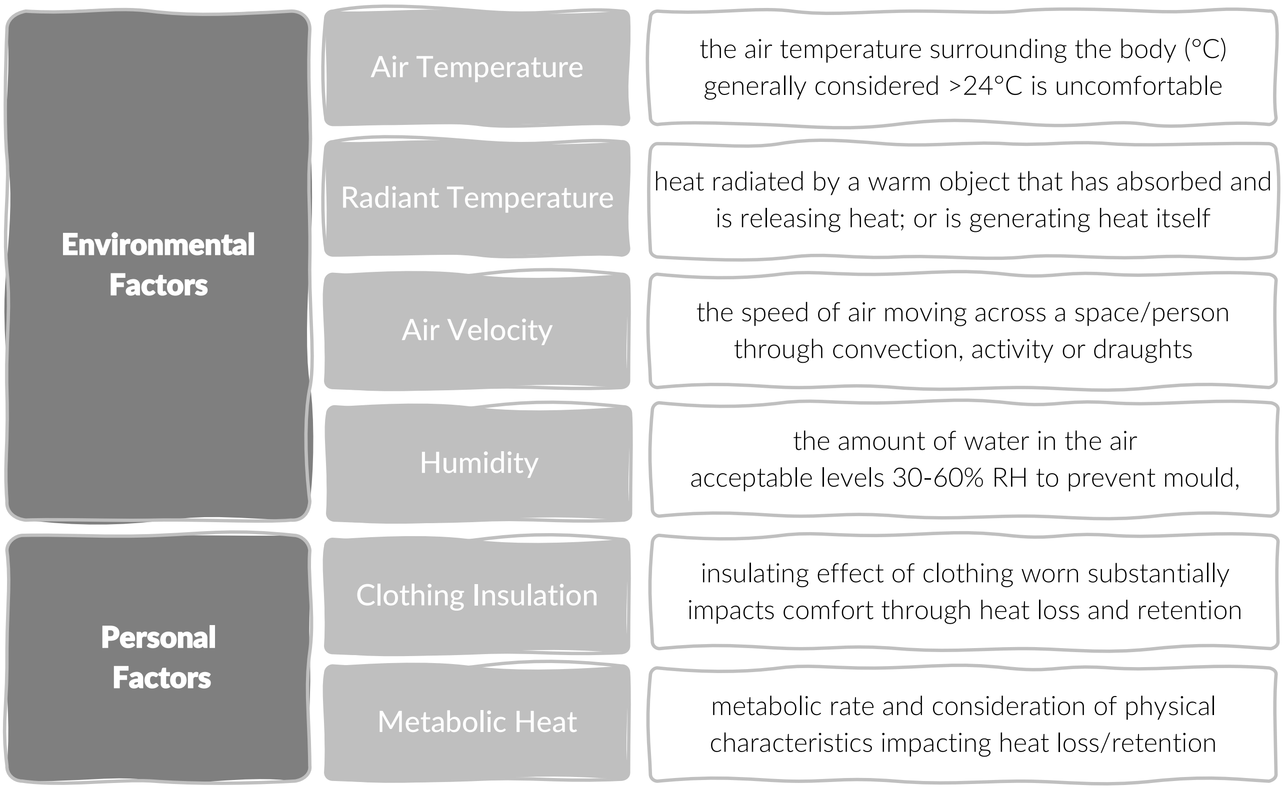


**Figure 2.9 –** Six basic factors underlying thermal comfort (Author's own 2019 based on HSE, no date)

### 2.6.5 Indoor Air Quality

As previously discussed, draughts have been shown to result in roughly 40% of heat loss in a typical building (Morgan 2018) and, as such, whether directly in an effort to reduce air infiltration, or indirectly as a by-product of a fabric related intervention, retrofit can impact airtightness and therefore, correspondingly, ventilation rates. Whilst there is currently a paucity of research, the importance of indoor air quality and its impact upon the occupant health is becoming increasingly recognised (Corbey, 2017).

As ventilation rates are reduced and the structure becomes increasingly sealed, concentrations of pollutants such as particulate matter, radon, carbon dioxide, carbon monoxide, formaldehyde, benzene and nitrogen dioxide are increased resulting in an increased risk to occupants, with the most vulnerable populations affected being children, the elderly, and people with existing respiratory disease (Frey et al. 2015). Reduced ventilation can equally lead to increases in relative humidity resulting in the outbreak of moulds at 60% relative humidity, leading to the proliferation of dust mites; whilst decreases in relative humidity to below 30% can cause sensory irritation (Broderick et al. 2017).

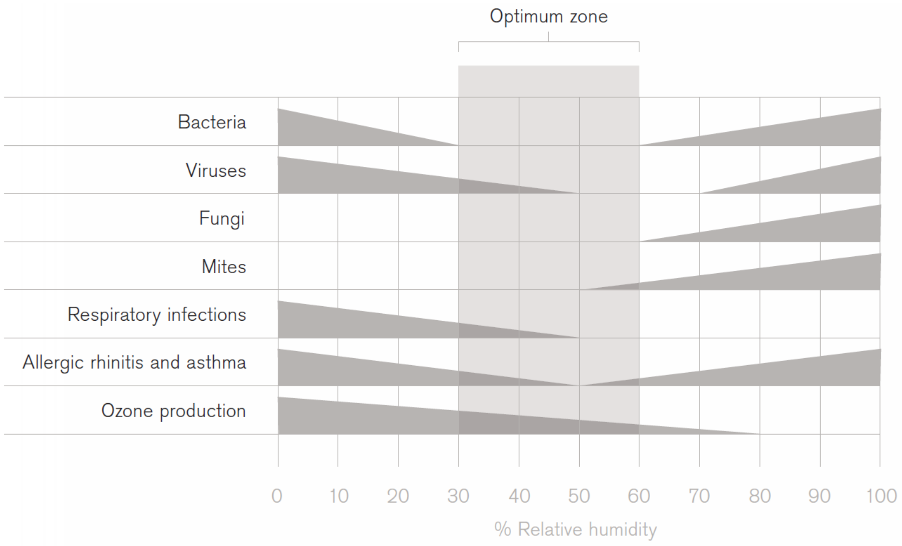


**Figure 2.10 –** Indirect health effects of relative humidity in indoor environments (Arundel et al. 1986)

In further examining the impact and the importance of ventilation on indoor air quality, a study recently completed regarding a programme to upgrade all the council stock in Carmarthenshire, to the Welsh National Homes Standard, involving 30,000 residents, over 10 years, with retrofitted heating systems, insulation and new windows and doors, found that whilst improved warmth decreased the number of hospital admissions, the largest improvement, with 39% fewer emergency hospital admissions for people over 60 living in improved homes, was shown where ventilation improvement had been carried out (de Selincourt 2019).

As such, whilst the available data clearly outlining the negative impacts as a result of poor indoor air quality remain largely outstanding, initial research and increasing focus has shown that it has a dramatic impact on occupant comfort and wellbeing and therefore is of paramount consideration during the retrofit process.

### 2.6.6 Case Study: Preston (de Selincourt 2018a)

The retrofit of small terraced traditional housing in Preston serves to illustrate the risks of poorly conceived and implemented retrofit with disastrous implications resulting in a raft of unintended consequences including: deterioration to interior surfaces, damp, black spot mould, fungal growth and water penetration, with resultant reported worsening of respiratory disorders and hospitalisation of some tenants.

The Preston retrofit scheme involved the application of external wall insulation and other measures to 390 homes, originally constructed around 1900, under the Community Energy Saving Programme (CESP).

Immediately following retrofit, occupants began to note a number of issues. In investigating the underlying causes, in addition to poor detailing and installation of the EWI, many of the properties were subsequently found to have narrow rat trap cavities, previously filled with cavity insulation, with defects associated with the application of the EWI leading to water penetration and saturation of the cavity insulation, resulting in water penetration at window heads, water exiting electrical sockets, damp and collapsed ceilings.

Adequate assessment of the properties in the initial instance would have enabled discovery of aspects such as the presence of cavity walls; the extent and detailing of the existing eaves and the need to increase the eaves projection; and existing ventilation rates and the presence of external fixings such a downpipes and meter boxes which required to be adapted, not worked around.

## 3.0 Retrofit Assessment

As we have seen it is critical to ensure the adequate assessment of a building prior to a fabric related energy retrofit measure in order to design out unintended consequences.

Retrofit assessment involves the detailed analysis of the building, incorporating its context, fabric – using a potential plethora of analysis tools, techniques and software – services and people in order to appreciate the hygrothermal dynamics of the building and how alterations in the physical properties of moisture, ventilation and heat will impact the structure and its condition.

### 3.1 Building Analysis

#### 3.1.1 Context

The primary influence on a building is always the environment to which it is exposed (Pender et al. 2014). A buildings context incorporates factors such as its condition, location, orientation, exposure, shading, climate, topology and topography.

The exterior environment is not necessarily bounded by any clearly defined parameters and the adequate assessment of the context of a structure will vary on a case-by-case basis, with a subjective assessment made on extending the analysis as far as required to consider any aspect which may affect the building.


**Figure 3.1 –** UK Exposure Zones (BRE 2002)

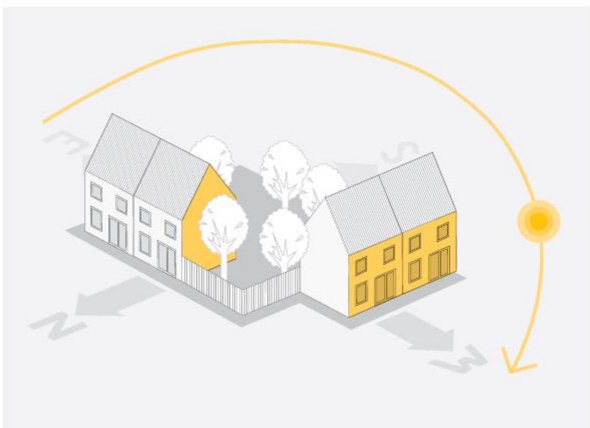

**Figure 3.2 –** Orientation and solar gain (NHBC Foundation 2012)

In addition to the external environment, the underlying condition of the structure is of fundamental importance as it is highly variable. It is paramount to ensure that a building does not have unresolved weaknesses, such as wet walls, cracks in walls, missing mortar, rotten timbers and other areas that could permit moisture ingress, that could increase the risk of faults developing post retrofit.

### 3.1.2 Fabric

Building fabric incorporates not only an appreciation of the underlying materials used in component assemblies such as walls, floors and roofs, although equally an appreciation of the construction and detailing, such as embedded floor joist ends or timber lintels.

Adequate assessment of the fabric requires both an appreciation of materials and construction, and an awareness of building physics concepts such as the moisture buffering potential for solid masonry walls and of the effect of the thermal mass of a structure having a stabilising effect on internal temperatures.

### 3.1.3 Services

Within the context of retrofit, building services predominantly focus upon three key areas: heating, lighting and ventilation. All of these will contribute to the building as a system and their existence, condition and ease of operation will have an impact upon the physical properties of heat, moisture and ventilation within a building.

It is important to appreciate both the extent of ventilation apparent within a building during assessment although equally the underlying ventilation strategy, whether it be passive stack, intermittent extract, mechanical extract, an alternative or any combination of ventilation means.

### 3.1.4 People

Whilst context, fabric and services are key considerations in an assessment process, people and their occupation and, critically, their use of a building are equally as, if not more, important. Occupants are key elements in the overall building system as they require certain conditions for comfort, operate energy-using lights and appliances, give off heat, produce moisture and carbon dioxide through respiration and produce moisture through activities such as cooking, bathing and drying clothes (British Standards Institution 2019b).

Internal conditions have the potential to vary massively dependent upon occupant numbers, although also behavioural habits and lifestyle. For example, heat levels and moisture generation will vary greatly from an individual elderly resident living in the same building to that of a young family and therefore the internal environmental conditions will vary greatly.

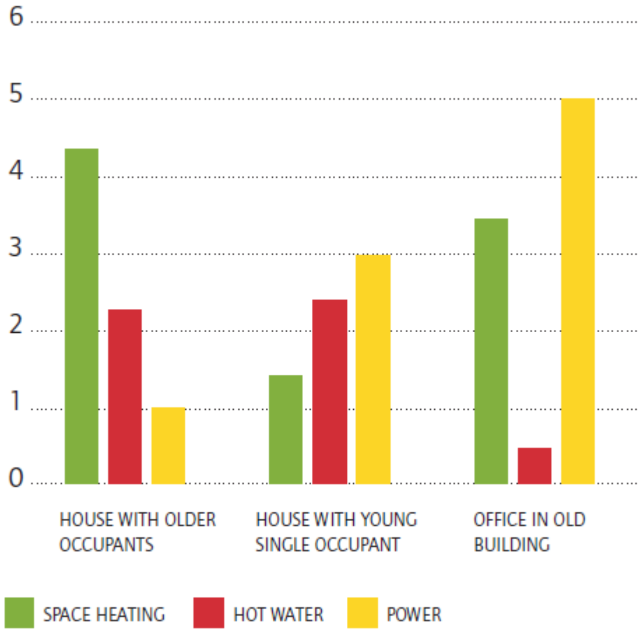


**Figure 3.3 –** Exemplar variability in energy use depending upon building and demographic (STBA 2015)

Although an appreciation of the people element of a whole house consideration is vital, it is equally potentially the most complex element due to its variable nature and the need to ensure that whilst a retrofit measure may be appropriate for current occupants, that it is equally appropriate for future occupiers.

### 3.1.5 Whole Building Assessment

As we have seen, there are a wide range of factors which are critical in gaining a sufficient detailed underlying understanding of a building undergoing retrofit although whilst these have been considered in isolation for the purposes of clarity, it is crucial these are considered as an integrated system. For example, in considering the implications of a factor such as wind driven rain, a buildings context such its topography, climate and exposure requires to be considered in conjunction with its fabric, as dense porous stone walls may be more susceptible to rain penetration and prolonged periods of damp, although how the occupant, or occupants, utilise the building and any possible services, such as heating, will fundamentally equally impact the rate of evaporation of moisture in the walls and how the building performs. This whole house approach and a detailed assessment of all aspects is therefore absolutely critical.

## 3.2 Analysis Tools

In order to gain a more detailed understanding of a particular aspect or component with which to supplement an underlying understanding of the building, its context and occupants, there exists a range of specialist analysis tools and techniques. These tools and techniques are generally segmented between destructive and non-destructive measures – those that do and do not require damage to be caused to the element to be inspected – and are principally focused upon either a closer examination of moisture, ventilation or heat loss.

The following section introduces a number of the most widely known and utilised tools for consideration in any pre-retrofit assessment.

### 3.2.1 Air Pressure Test

Air pressure tests, also known as fan-pressurisation or blower door tests, use very high indoor pressures to induce air exchange, enabling the determination of airtightness and the detection of exposed or concealed air infiltration, such as gaps around windows or doors or at interfaces between building assemblies such as floors and walls (Pender et al. 2014). They are a non-destructive assessment tool and are often combined with smoke testing to clearly visualise patterns of air exchange and movements.

**Figure 3.4 –** An air pressure test (Morgan 2018)

In order to undertake a test, a large powerful compressor (fan) is typically temporarily inserted within the frame of an external door opening, with all other external doors and windows closed, and with any extractors disabled. The fan either introduces or extracts air at a set pressure of 50 pascals, resulting in air being either pushed out, or drawn into a building via gaps and allowing this to be monitored via a pressure gauge to derive an air permeability reading expressed in $m^3/hr/m^2$ at a standard pressure difference of 50 pascals.

### 3.2.2 Thermal Imaging

Thermal imaging, also known as infrared thermography, is a type of non-destructive investigation that permits rapid imaging of temperature variations across large surface areas via use of a thermographic camera (Young 2015).

Thermographic cameras function similar to digital cameras, although detect infrared radiation which correlates with the temperature of an object, with the camera converting the intensity of the radiation to a visible image or thermogram. The warmer the object, the more radiation emitted. The camera records the radiation intensity for any one location and dynamically converts the intensity to a mean surface temperature, which in-turn is mapped to a temperature scale to produce a radiometric image. The temperatures recorded by the camera are normally accurate to within 1-2°C, provided conditions have been set correctly.

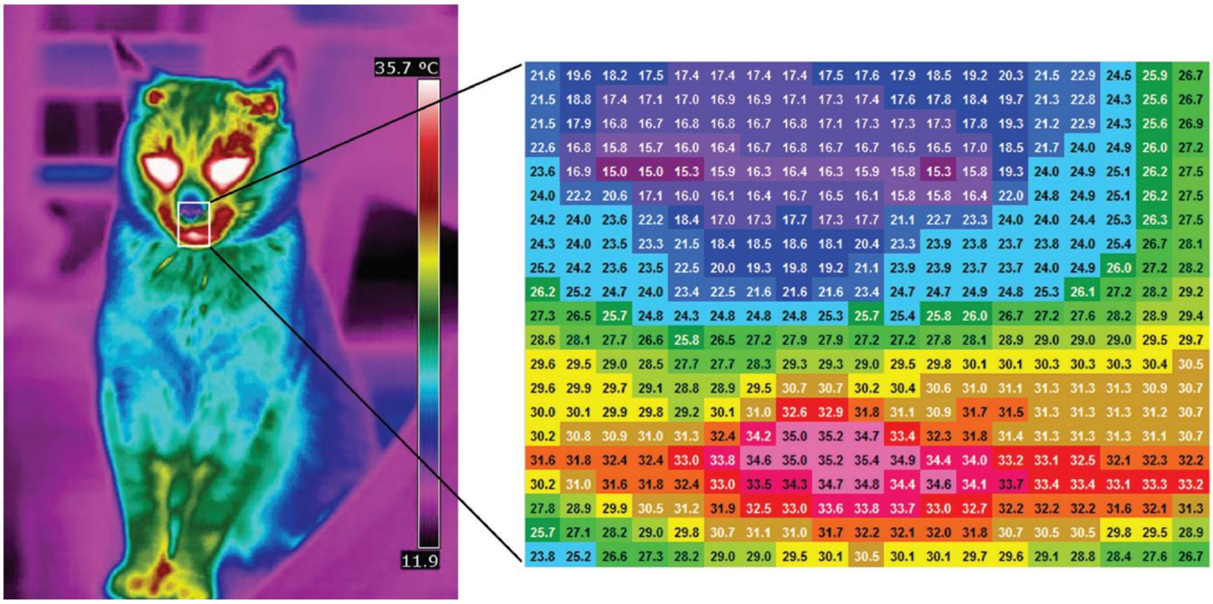


**Figure 3.5 –** Correlation between a thermal image and a temperature scale (Young 2015)

Thermography has a wide range of applications although can be an extremely useful tool in the survey and investigation of traditional buildings enabling assessment of heat loss, damp, airtightness and thermal bridging (see Figures 3.5 – 3.8, respectively) by identifying significant temperature variations, inconsistencies or anomalies.

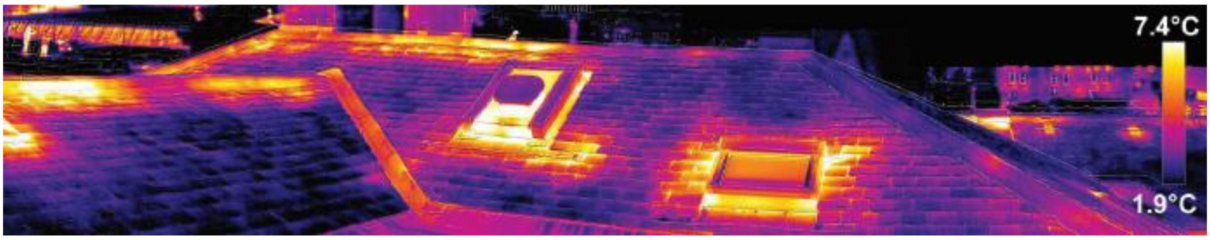


**Figure 3.6 –** Thermography: Heat loss visible to a roof with gaps in insulation identified to the ridge line (Young 2015)

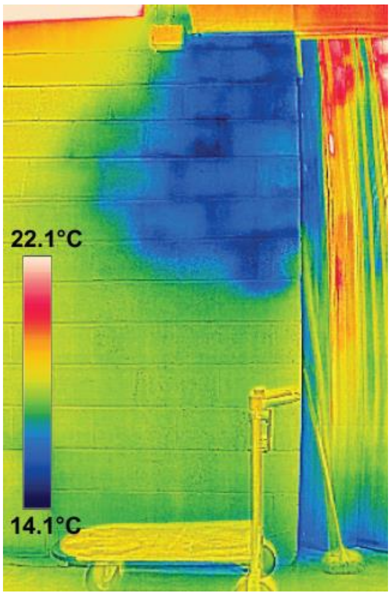


**Figure 3.7 –** Thermography: identifying damp, with a leakage to a pipe (Young 2015)


**Figure 3.8 –** Thermography: identifying air tightness with draughts impacting surface temperatures visible (Young 2015)

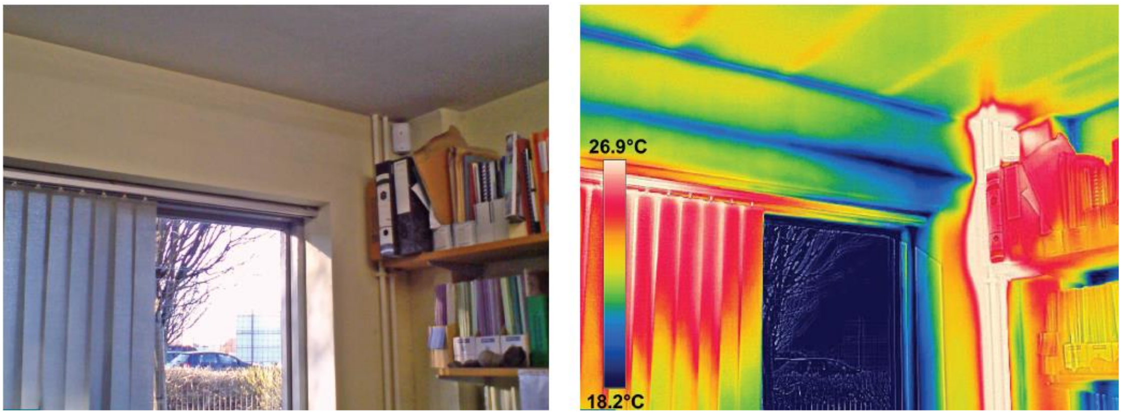


**Figure 3.9 –** Thermography: identifying thermal bridging (Young 2015)

Whilst useful, as highlighted by Young (2015), the images produced with a thermal camera can easily be misinterpreted or manipulated and can sometimes be misleading. A range of environmental factors, including: internal and external air temperature, relative humidity, wind speed, mist or fog, will impact the captured data, including other aspects such as reflections, angle of view, recent substantial changes in air temperatures and camera parameters such as an emissivity value which is required to be set dependent upon material type to determine what proportion of thermal data is attributed to surface temperature as opposed to reflected infrared radiation.

All of these factors require experience and knowledge of the operator to know how to use the equipment, be aware of the environmental conditions which could impact the output data and even make informed decisions regarding when data should be captured, i.e. it may be necessary to capture images at particular times of the day or upon instigating particular conditions in order to derive sufficient temperature contrasts.

Ultimately, thermography represents a useful tool, although as highlighted by Young (2015), diagnosis of a problem cannot be achieved with thermography in isolation, especially for complex structures.

### 3.2.3 Borescope

Borescopes are a destructive optical investigation tool consisting of a camera attached to a flexible or rigid probe which is in-turn attached to an output device such as a small colour screen and is utilised to inspect voids, such as cavities and sub-floor voids and may facilitate the more detailed investigation of an area, defect or form of construction.

They may, for example, permit the inspection of a wall cavity in order to determine the form of construction, the approximate depth and presence of any insulation and any defects apparent within the cavity, such as the incorrect installation of wall ties channelling water to the inner leaf, or the presence of debris within the cavity.

### 3.2.4 *In situ* U-value Measurement

A U-value provides a figure for the overall performance and heat transfer through a building element, measured in W/m$^2$K.  Given the variability in thermal performance of traditional building materials (Baker 2011), an *in situ* U-value measurement can provide a much more accurate assessment of the thermal performance of a building element.


**Figure 3.10 –** A HFP01 heat flux plate (Huskseflux [no date])

An *in-situ* U-value assessment is a non-destructive means of measuring thermal transmittance in site-specific, pre-existing building elements, following the principles set out in prEN 12494.  The measuring of the *in situ* U-value of an external wall involves the installation of a heat flux plate attached to the interior surface of the wall, with a data logger to record readings and the application of an algorithm devised by Dr Paul Baker of the Glasgow Caledonian University. The algorithm takes the cumulative average surface temperature difference across the wall and divides this by the cumulative average of the heat flux figure, with allowances for standard internal and external surface resistances and a small correction applied for the resistance of the heat flux sensor, with the reciprocal of this total taken to convert the resistance to a U-value (Rye and Scott 2012).

### 3.2.5 Diagnostic Monitoring and Data Loggers

Diagnostic monitoring permits the observation of environmental conditions such as temperature and relative humidity and can be captured at set intervals via data loggers.


**Figure 3.11 –** Tinytag data loggers (Gemini Data Loggers [no date])

Whilst monitoring is commonly used in post-retrofit applications for the purposes of completion of post occupancy evaluations and for comparison of actual results with initial design levels, monitoring pre-retrofit permits the detailed scrutinisation of conditions that may assist in definitively confirming occupant behaviour, such as use of heating controls, or the generated levels of moisture vapour and relative humidity that may be impacted following retrofit.

## 3.3 Modelling Software

Although a large proportion of assessment is derived from observation of context and condition, with this being supplemented with more specialist analysis tools, an increasingly developing area concerns that of software modelling used for very detailed analysis of particular components or scenarios.

As with analysis tools, a range of software exists to assist in assessment, with an overview of a number of the most widely utilised modelling software briefly covered in the following section.

### 3.3.1 Hygrothermal Modelling

In looking to gain a more detailed technical understand of the risks associated with condensation, a key underlying document, used almost exclusively within the industry (Rye and May 2012; Little et al. 2015) is BS 5250:2011 *(Code of Practice for the Control of Condensation)*, which provides advice on the avoidance of internal surface and interstitial condensation caused by the movement of water vapour by diffusion through the building envelope from the interior to the exterior. Within BS 5250:2011, explicit reference is made to a further standard, BS EN ISO 13788:2012 *(Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation)* for a means of calculating risk using the Glaser Method. However, use of this methodology in traditional solid walled buildings, which store large amounts of water in their fabric, has been shown to be insufficient as no account is taken of rain impacts and solar gain on the outside surface, liquid water movement and the effect of moisture on the thermal and moisture transport properties of materials (STBA 2015; King 2016). As a result, this methodology in traditional buildings is deemed to be potentially damaging, leading to considerable fabric decay and risks to human health, with concern that problems arising from incorrect assessment may occur and become apparent only after some time (Rye and May 2012).

An alternative standard, BS EN 15026:2007 *(Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation)*, which openly highlights the limitations of the Glaser method, was developed do address these issues (Little et al. 2015). BS EN 15026:2007 sets out the mandatory criteria required to be considered by simulation software to predict one-dimensional transient heat and moisture transfer in multi-layer building components, exposed to transient climate conditions on both sides.

Hygrothermal modelling software allows mitigation of an element of risk associated with retrofit by permitting the detailed dynamic simulation of heat and moisture with a range of energy retrofit approaches and materials, thereby helping analyse which forms of intervention would lead to unintended consequences in the form of interstitial condensation, degradation of building fabric and impacts to indoor air quality. The use of hygrothermal simulation tools has increased in response to the growing number of reports of moisture problems after retrofit (Rhee-Duverne 2019).

Whilst a number of hygrothermic analysis tools exist – over 40 were identified in a research analysis project in 2003 (Canada Mortgage and Housing Corporate 2003) – the two most widely known tools, which adhere to BS EN 15026:2007, are DELPHIN and WUFI, with WUFI being the recognised industry leading tool (Little et al. 2015).

WUFI Pro (Wärme und Feuchte instationär – Transient Heat and Moisture) is a software package initially developed by Hartwig Künzel at the Fraunhofer Institut Bauphysik in Germany, used to simulate hygrothermal modelling of the movement of heat and moisture through buildings (Baker 2015).

WUFI is pre-populated with a material database of components, predominantly of German origin, with the user required to import materials from the database – or create new – in order to build-up a component assembly permitting modelling. Each material within the database is afforded a range of properties, such as: porosity, thermal conductivity, density and a water vapour diffusion resistance factor, which permit sufficiently detailed modelling within the software.

Once the component assembly is formed, the user is required to input additional contextual data, including: orientation, pre-existing built-in component moisture and climate (i.e. relative humidity, temperature, wind speed and direction, rainfall and solar radiation), to allow the simulation to be run with results outputted in a graphical interface.

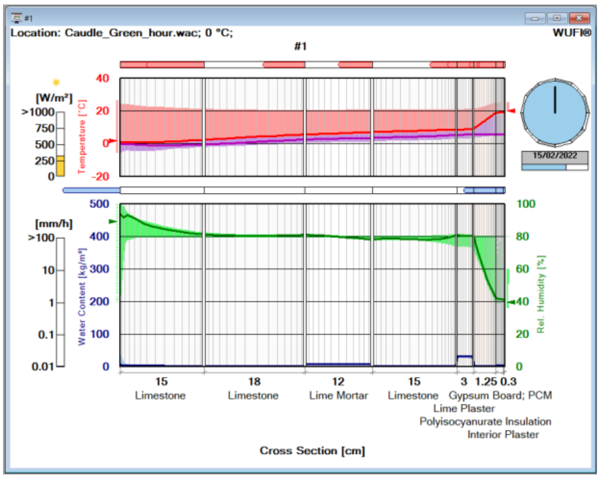


**Figure 3.12 –** A WUFI simulation (Author's own 2019)

Both a 1-dimensional (1-D) – WUFI Pro – and a 2-dimensional (2-D) – WUFI 2D – variant of WUFI are available. WUFI 2D is considerably more complex and used where 2D analysis is more suited to complicated geometries, such as building corners, window locations, and foundation connections. For the majority of cases, and following analysis of the software variants by Baker (2015), WUFI Pro is regarded to perform adequately for the purpose of predicting risk in more common component assemblies.

### 3.3.2 Component Assessment

Component assessment software permits the modelling of heat-transfer effects in building components such as windows, walls, foundations, roofs, and doors where thermal bridges are of concern. The most prevalent and well-known component assessment software for thermal simulation is THERM, developed by the Lawrence Berkeley National Laboratory.

THERM is a finite element analysis software tool that models two-dimensional steady-state heat flow, allowing evaluation of the energy efficiency and local temperature patterns of materials which may relate directly to problems with condensation, moisture damage, and structural integrity (Berkeley Lab [no date]).

THERM allows graphical presentation of results in a number of ways including isotherms, although also as colour infrared which permits the thermal principles and variants to be clearly identified.

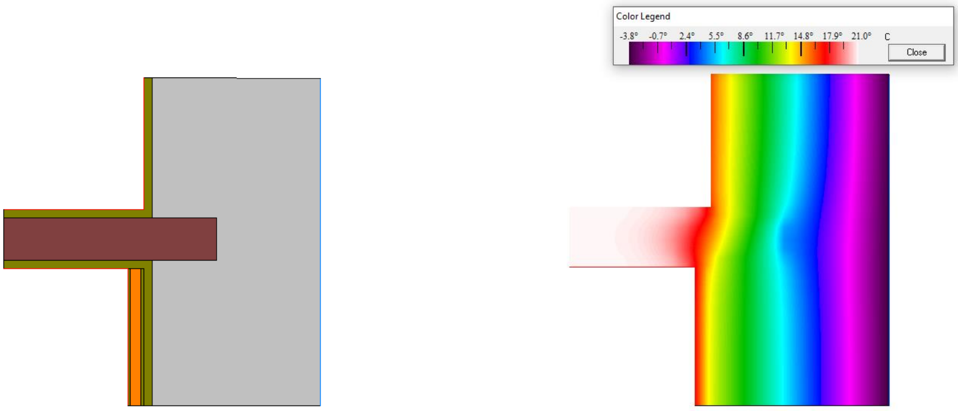


**Figure 3.13 –** THERM temperature gradient modelling of a solid wall with application of IWI (Author's own 2019)

## 4.0 A Formulaic Assessment Framework and Process

Following the introduction of the concept of retrofit, the pertinent aspects of building physics, unintended consequences and an overview of some of the relevant considerations and tools in retrofit assessment, it is possible to consider the development of a framework and process to enable sufficiently detailed assessment of domestic small-scale traditional buildings in order to design out unintended consequences.

In considering the use of these tools, it is important to reiterate the objective of investigating a process for small-scale traditional retrofit and therefore appreciate the boundaries within which this process must operate. These boundaries specifically reflect the constraints of budget, time, complexity and even practicality, with these constraints considered both in isolation of each individual assessment tool, although equally the combined cost and time required to incorporate all additional assessment tools. As introduced at the outset of this thesis, previously high-profile and well documented retrofits have involved modelling and assessment of structures by industry leading experts for a period of up to three years prior to intervention, with proportionately almost unlimited budgets and with unfettered access to model and assess the structures in detail – all of which is appreciably far beyond the realms of feasibility for a typical domestic retrofit.

As such these boundaries are absolutely critical in appreciating the feasibility of use of these tools and whether a combination of budget, time, complexity and practicality – despite the tools appearing useful – may preclude their use altogether. Furthermore, it is equally relevant to indicate that if these tools are deemed vital, yet they are not feasible given the scale of the works, then the risk profile of an energy related retrofit under particular conditions may become untenable and preclude retrofit altogether.

### 4.1 The “Retrofit Survey”

As we have seen, and as highlighted by Pender et. al (2014), the primary influence on a building is always the environment to which it is exposed. As such, at the outset of any fabric related energy retrofit assessment process, it is essential to initially gain an appreciation of the external environment incorporating an amalgamation of location, orientation, exposure, shading, climate and the surrounding topology and topography. These factors are critical in permitting a detailed underlying assessment of the interplay of moisture sources, such as precipitation, wind driven rain and ground drainage patterns; ventilation sources from wind; and, heat from solar gain.

Once a sound appreciation of the context of the structure is understood, this can be augmented with details regarding the structure itself: its fabric, construction and condition. This enables consideration of aspects such as porosity of the surface of external stone walls (rate of rain absorption), the extent of any roof overhang (exposure and drying potential), the thickness of the wall (capacity to store moisture), vulnerable points such as window frame seals, cills, copings and abutting garden walls (potential for water ingress) (Smith 2017). All of this can be supplemented with building pathology to understand the condition and defects associated with the existing structure, such as wet walls, staining, cracks in walls, state of repair of pointing or render, rotten timbers or other areas permitting moisture ingress and any high external ground levels.

Lastly, it should be necessary to determine the presence and efficacy of services present within the structure, such as heating and ventilation, and the behavioural habits and lifestyles of occupants to understand how these services are utilised and may therefore impact physical conditions within the property.

Ultimately, the augmentation of contextual information such as orientation, exposure, shading and knowledge of driving rain, coupled with fabric related aspects such as porous stone walls, construction details such as knowledge of embedded timber floor joists or lintels, condition details such as defective pointing to solid masonry walls and service and occupant related aspects such as heating sources, location and use of this heating, enables a whole building assessment revealing, in this scenario, the potential for timbers becoming exposed to risk of decay as a result of prolonged saturation of porous stone walls, with reduced drying potential by the lack of use of heating by the occupants. These factors will thereby influence retrofit design solutions, removing those which may exacerbate risk and result in further fabric decay to the structure. It may equally permit determination that the fabric energy related retrofit of an aspect of a building, such as wall insulation, is fundamentally unsuitable given the nature of the building, its occupants and its external environment.

Whilst we have outlined the importance of undertaking a whole house assessment process, this process omits one final crucial element relating to those retrofit specific considerations impacting the feasibility of a particular form of intervention. These retrofit specific considerations include aspects such as the detailing and extent of any eaves overhang, internal or external service penetrations or fixings, internal fixings such as a cornice or fitted wardrobes – all of these aspects will make an extremely relevant contribution to the practicalities of undertaking any retrofit.

The combination of all of the above relevant aspects goes beyond the remit of any one single process or document evident in the industry at this moment in time and therefore supports the creation of the concept of a "retrofit survey". This would not only entail the completion of a building survey – akin to an RICS level three survey (RICS 2016) – although would equally include a more detailed consideration of context, services, occupants and those retrofit specific considerations.

Whilst outside the scope of this thesis, this retrofit survey should equally include heritage considerations, such as the significance of the structure in accordance with BS 7913 (British Standards Institution 2013), although equally planning and statutory considerations and protections such as listed buildings, conservation areas and areas of outstanding natural beauty, all of which would have an impact upon the energy retrofit strategy.

Irrespective of the nature of a fabric related energy retrofit, given the criticality of this aspect, the concept of a retrofit survey is considered a mandatory component of a whole house analysis framework and process. Given the lack of detail regarding any existing systemic process, Appendix B proposes a retrofit survey pro-forma, intended to capture relevant detail.

An additional relevant consideration in the undertaking of the retrofit survey is that of the competence of the individual undertaking the survey and the need for sufficient skills, knowledge, experience and training. As previously described, given the core of this survey is akin to an RICS level three survey, knowledge of building pathology, construction and conservation is deemed to be obligatory, with an added requirement for an appreciation of design, detailing and an understanding of building services. As such it is arguably necessary for a professional to be a number of a body such as the RICS, CIOB, ARB, CIAT or CIBSE and have relevant building-related knowledge.

## 4.2 Detailed Assessments: Moisture, Ventilation & Heat

Whilst the completion of a retrofit survey can be regarded as a mandatory baseline requirement in pre-retrofit assessment, it may not necessarily permit a sufficiently detailed analyses of the structure and specifically the critical aspects of moisture, ventilation and heat to enable unintended consequences to be adequately designed out. As such, it is necessary to consider the range of tools and software previously introduced and if these should form a mandatory, or optional component of our assessment framework and process.

### 4.2.1 Moisture Assessment

Moisture is widely regarded to those within the industry to be the single largest most damaging factor at play (Brand 1995); therefore, adequate detailed assessment of its presence and particularly that of the build-up of interstitial condensation in the undertaking of energy related retrofit is vital.

As we have previously seen, given the limitations of BS 5250:2011 and BS EN ISO 13788:2012 in their practical applications in assessing moisture build-up in traditionally constructed buildings, if a more detailed hydrothermal assessment is required, this should be undertaken by a tool adhering to the BS EN 15026:2007 standard, such as WUFI.

Whilst WUFI is recognised as making significant advances over previous prescribed methodologies, as recognised by King (2016), there are a number of challenges with adoption of WUFI due to three main considerations: quality of input data, cost and complexity.

The quality of the output from WUFI is predicated the quality of the input data. One of the largest hurdles outlined by Rhee-Duverne (2019) is that whilst WUFI has a database of existing materials, these are predominantly of German origin and not calibrated for the proliferation of the various materials found in the UK. The risk of inaccuracy associated with the use of a generic materials selected from the WUFI database is of greater significance in the modelling of traditional structures, as traditional buildings were inherently constructed from those local vernacular materials to hand, each with their own specific properties, meaning that, for example, the properties of a limestone used in construction of a solid external wall in one part of the country, may vary greater in properties of a limestone from another section of the country. Whilst it is possible to input bespoke property specific samples following extraction of materials sent for laboratory analysis – with Historic England finding that uncertainties of the predictions are greatly reduced when accurate material property data are used (Baker 2015) - this process is deemed complicated and expensive in the context of small-scale domestic retrofit.

In addition to sufficiently representative material properties, WUFI equally requires population of external weather data using software such as Meteonorm, Energy Plus or ASHRAE; however, it is unclear how realistic this data is for actual conditions as the weather files created use triangulation from the nearest meteorological stations and extrapolate the results, with these deemed to be harsher than actual conditions (King 2016). As with material samples, detailed external weather data can be acquired from the Met Office, although this has been estimated by King (2016) to be in the region of £8,000 and therefore prohibitively expensive for small-scale domestic retrofit.

Despite the restrictions highlighted by King with data obtained from software such as Meteonorm, given the lack of any UK related weather data included by default within WUFI, it is at least necessary to obtain weather data for the nearest available location and therefore this would mandate the use of software such as Meteonorm. Meteonorm is not complicated software to use, although a single licence to use the software at the time of writing is roughly £500.

In addition to limitations regarding quality of material and weather data and the cost associated with obtaining bespoke data, is that of the cost – both of the software itself and adequate training. A 1-year licence to WUFI Pro 6.4, the latest available version at the time of writing, is £780, with a further £700 cost for a 2-day WUFI training course (all excluding VAT), run by the most widely recognised WUFI expert, Joseph Little. This would require a total overall investment of around £2,000 in order to use WUFI; however, whilst not insignificant within the context of small-scale domestic retrofit, it is recognised this cost could be spread across multiple domestic projects and therefore become more palatable.

With respect to complexity, whilst inputting of WUFI data and overall use of the software is not time consuming, WUFI is a complex programme that requires a good understand of building physics to operate effectively. It can be very easy to enter the wrong parameters producing misleading or inaccurate results. Modelling of conditions by Historic England demonstrated the significant effect of the accuracy of simulations by estimating correct WUFI parameter values for the rain adherence fraction, which has an influence in driving rain calculations, and the amount of solar radiation and degree of shading on a wall (Rhee-Duverne 2019).

In summary, despite the limitations of the existing material and weather datasets; the cost of the tool; complexity of its operation; and despite simulations not being viewed with complete confidence, given the risk associated with energy retrofit, the implications of failure and the more severe drawbacks of less refined BS methodologies it remains a useful tool to provide some appreciation of risk.

As commented by Smith (2017) in his consideration of WUFI, there is no guaranteed way to fully design out risks although a cautious approach should be encouraged; therefore, even if outputs are not entirely accurate, they can be utilised to apportion a degree of risk. As such it is believed WUFI should become a core mandatory component to assist in designing out unintended consequences in the energy retrofit of traditional buildings, with it being deemed overly risky within the context of traditional buildings, with complex hygrothermal behaviour, to omit more detailed analysis entirely.

### 4.2.2 Thermal Bridging Assessment

As previously described, thermal bridging can result in a number of detrimental impacts to building fabric and occupants, with detailed component assessment software such as THERM assisting in the assessment process.

Whilst THERM is a freely available tool, and is not overly complex to learn and operate, its mandatory use as a part of the assessment process is questionable. It is argued that use of sufficient insulation and detailing at key junctions and recognised thermal bridges should form a mandatory aspect of any competent designer's standard methodology and therefore detailed additional modelling – unless required in the interests of attaining particular standards or accreditation – may not be necessary. However, it is accepted that the tool may become more useful or relevant if the configuration of the building undergoing retrofit is such that physical limitations in the application of sufficiently deep insulation are prohibitive, i.e. at window reveals, with modelling thereby providing an element of assurance.

Whilst THERM is a freely available tool, the time taken to model each potential thermal bridge in the context of a small-scale typical domestic retrofit is deemed to be considerable and thereby its routine application in a typical domestic retrofit is potentially prohibitive. However, as with WUFI, given the potential implications in omitting sufficient analysis and the resultant implications for heat loss, mould and impacts to IAQ; and, given the subjective nature and interpretation of 'sufficiently deep' insulation, it is believed THERM should form a mandatory component in the analysis.

### 4.2.3 Ventilation and IAQ Assessment

As we have seen, without adequate consideration of ventilation and the overarching ventilation strategy, any retrofit measure – whether directly intended to reduce air leakage, or resulting as a by-product of the retrofit of an associated fabric element – will likely result in a reduction of natural infiltration which may have been providing adequate ventilation, resulting in higher concentrations of indoor pollutants, thereby leading to degradation in IAQ and health risks to occupants; and, resulting in higher rates of humidity leading to increased risk of fabric decay. As such, ventilation is an absolutely critical consideration in the retrofit process to design out unintended consequences, irrespective of the scale of the retrofit.

Whilst the undertaking of an air pressure test is a specialist procedure, exposure to the complexities of the process are limited given the need for an independent specialist to undertake the test. Furthermore, despite it being specialist in nature, it is equally a relatively straight forward procedure, invariably taking less than two hours to complete. In addition, the cost of completing an air pressure test as at the time of writing is roughly £250 excluding VAT. Therefore, even within the context of small-scale typical retrofit, the undertaking of an air pressure test is deemed highly feasible.

Despite the undertaking of an air pressure test being feasible within the bounds of a typical domestic retrofit, and despite the importance of adequate ventilation post-retrofit, the incorporation of an air pressure test within the assessment framework is disputable. It is evident that allowances for adequate ventilation must form a component of any retrofit solution and arguable that this should be met without the need for an appreciation of a detailed air change metric. As such, the use of an air pressure test is believed to be an optional component of the framework, only becoming mandatory if required in order to prove adherence to a particular standard or accreditation such as Building Regulations, EnerPHit, or the AECB Silver Standard.

#### 4.2.4 Overheating Assessment

As previously discussed, overheating can not only impact thermal comfort, although equally lead to more serious health implications and even mortality amongst certain cohorts. In recognition of the growing evidence, the Good Homes Alliance (2019) have proposed a simple one-page early stage overheating risk tool (Appendix C) to assess overheating risk in residential schemes at the early stages of pre-detail design.

The tool requires the selection of the most appropriate multiple-choice option for key factors reducing the likelihood of overheating, which derives a total points score, and then for this apportioned score to be deducted from a similar array of key factors likely to increase the likelihood of overheating. Depending upon the derived total score, the tool provides a high-level indication as to whether overheating is low, medium or high risk. If the tool indicates a low level of risk, it merely advises the project continues under the specified conditions; however, if a medium or high risk is determined, the tool advises of the need to carry out a more detailed assessment using the prescribed methodology within TM59 (CIBSE 2017), or via another suitable dynamic modelling tool.

Although this tool is new and therefore empirical quantitative or qualitative data to substantiate its performance remains outstanding, it remains an extremely simple, free, method with which to provide an indicative view of overheating. As such it is believed the Good Homes Alliance tool should form a mandatory component of the assessment framework, with – as advised by the tool – further dynamic modelling via either TM59 or a tool such as the Passive House Planning Package (PHPP) becoming necessary only if a medium or high risk of overheating is determined.

### 4.3 Additional Tools

In addition to the underlying concept of a retrofit survey and the application of more detailed modelling tools to better understand the dynamics of moisture, ventilation and heat, it is recognised that a wide range of other tools, such as borescope or thermal imaging camera could be utilised throughout the assessment process. However, these are not deemed mandatory and should be regarded as discretionary additional tools utilised by a professional as they see fit throughout the assessment process.

With respect to in situ U-value measurements and additional tools such as PHPP, unless a tool such as PHPP is specifically prescribed as a result of the aforementioned overheating assessment, these tools are deemed generally beyond the scope of a framework with a restricted intention of designing out unintended consequences. Rather these are seen as relevant tools to be utilised if either accreditation is required, e.g. EnerPHit, or the AECB Silver Standard, or if the professional or homeowner requires a more empirical view of the pre and post energy performance of the structure. Similarly, use of diagnostic monitoring and data loggers are deemed predominantly only relevant in the context of Post-Occupancy Evaluation (POE), or as a means to monitor the performance of the retrofit so as to iteratively enhance the design and performance of future retrofits.

### 4.4 The Proposed Process

Following a more detailed consideration of the various tools, a prescribed process to permit adequate assessment and allow unintended consequences to be designed out in the energy retrofit of small-scale domestic buildings is proposed as below.

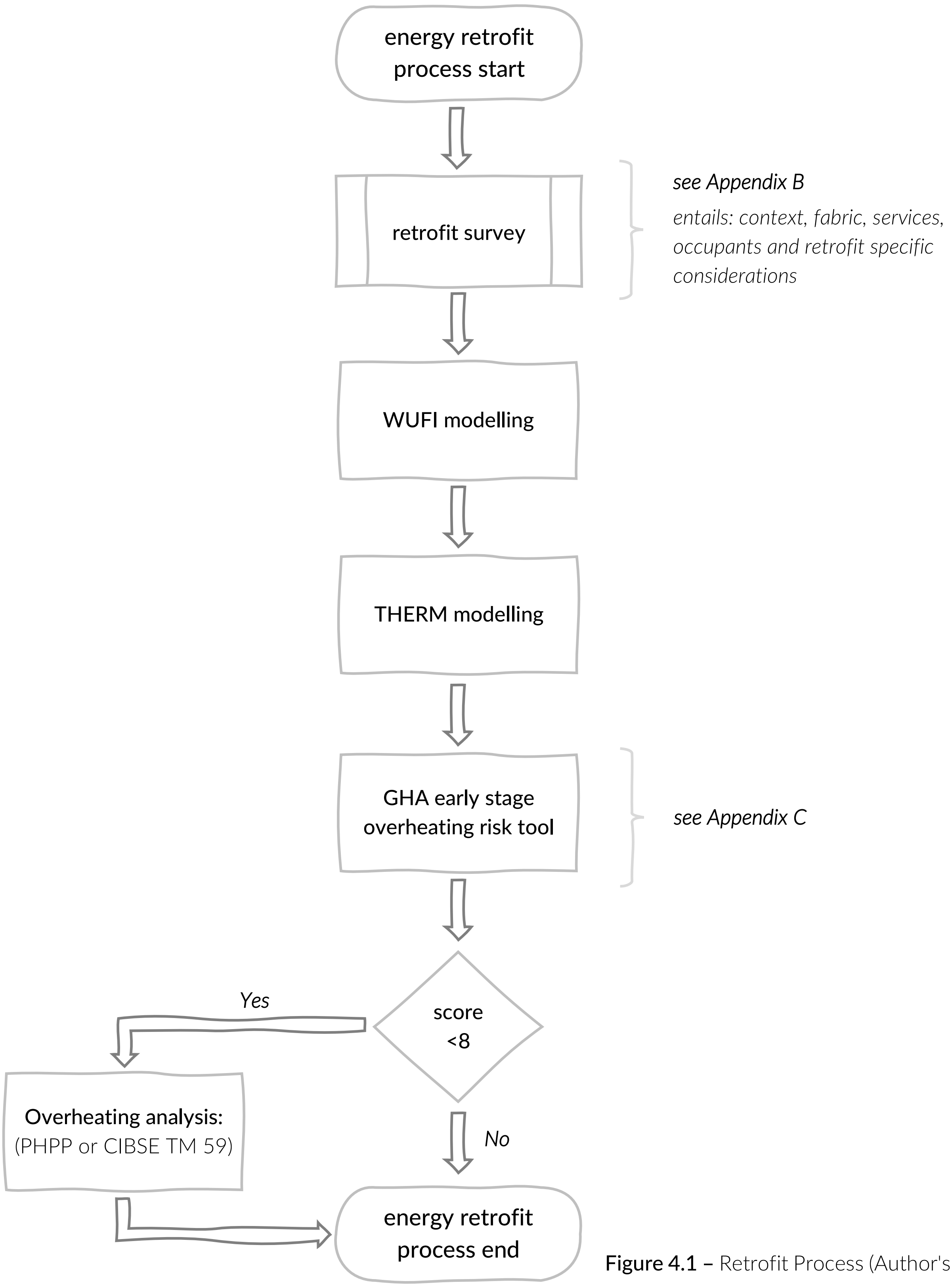


**Figure 4.1 –** Retrofit Process (Author's own 2019)

## 5.0 Case Studies

### 5.1 Case Study 1 – Cumberworth, West Yorkshire

This domestic property located in Cumberworth, West Yorkshire, and being situated in a very windy and exposed area on the top of the Pennines, comprises a 4-bedroom, 150m$^2$, semi-detached house, consisting of a traditionally constructed Victorian barn, which was subsequently converted, with a later 1990s cavity walled extension.

**Figure 5.1 –** Case Study 1 – Cumberworth (Green Building Store 2017)

The solid walls to the original barn were of 450mm thick natural stone, clad with natural Yorkshire stone with rubble infill. The cavity walls to the 1990s extension were 300mm thick, consisting of 150mm coursed Yorkshire stone, a 50mm clear cavity, with a 100mm lightweight concrete 'poly-back' block to the inner leaf – the block having a 30mm thick polystyrene board bonded to the block, thereby mandating separate wall insulation strategies.

Due to planning restrictions and a need to retain the external stone aesthetic, the property was retrofitted with IWI. An initial condition survey was completed to highlight those defects which required attention. Given specific concerns with respect to moisture, with wind driven rain given exposed location; the lack of a damp-proof course to the traditional barn resulting in concerns of rising damp from groundwater; and interstitial condensation following application of the IWI, WUFI was used to complete a moisture risk assessment for both the solid stone and cavity wall. IWI to the solid stone walls consisted of a weak sand and cement parge coat, with 100mm of TecTem (a Knauf perlite insulation board) and a lime plater internal finish. IWI was similarly applied to the internal face of the cavity walls, consisting of 100mm thick mineral wool bats fixed between timber studding, finished with plasterboard and a gypsum-based plaster finish.

**Figure 5.2 –** Case Study 1 – Cumberworth (Green Building Store 2017)

To address concerns with thermal bridging, 10mm custom made Vacuum Insulated Panels (VIPs) were used at window and door reveals, although no modelling of this was completed using software such as THERM, and instead the application of 10mm to the reveals was deemed to achieve a satisfactory U-value to reduce risks.

An air pressure test, PHPP and a thermal imaging camera were equally used as a part of the retrofit. However, PHPP was purely used to permit modelling of likely energy use post retrofit, with the air pressure test used to allow values to be inputted into PHPP and compare before and after results. The thermal imaging camera was only used in a POE capacity, to determine deficiencies with installation of the IWI and any airtightness detailing issues to permit iterative improvements for future retrofits.

**Figure 5.3 –** Case Study 1 – Cumberworth (Green Building Store 2017)

## 5.2 Case Study 2 – The Barrel Store, Gloucestershire

*Whilst this case study concerns a commercial retrofit, given the extremely limited extent of available case studies for retrofit of traditional structures and given its nature, the retrofit of The Barrel Store is regarded as being sufficiently relevant to allow parallels to be drawn with domestic retrofit.*

The Barrel Store, located in Cirencester in Gloucestershire, underwent a scheme of retrofit in 2016 to become the first you hostel in the UK to be certified to the Passivhaus EnerPHit standard.

**Figure 5.4 –** Case Study 2 – The Barrel Store (Passvihaus Trust 2018)

The Barrel Store is a traditionally constructed Cotswold vernacular building consisting of solid limestone walls with pitched roof slopes. The building was originally constructed in the 1820s as a warehouse to serve an adjacent brewery. Over the passage of time, it became derelict and was converted into a theatre in the 1970s, operating for several decades before closing. New Brewery Arts, the owner and a charity, decided to convert the building to a youth hostel, appointing Potter & Holmes Architects with Greengauge – a building physics, services and design specialist – as consultants (Passivhaus Trust 2018)

The Barrel Store was retrofitted with IWI consisting of a lime plaster parge coat being applied to the internal stone walls, with a continuous 100mm thick rigid woodfibre insulation layer fixed to the masonry. A new timber structure, thermally separated from the walls and floor, was constructed against the rigid woodfibre insulation, then being filled with a further 80mm thick flexible wood fibre insulation.

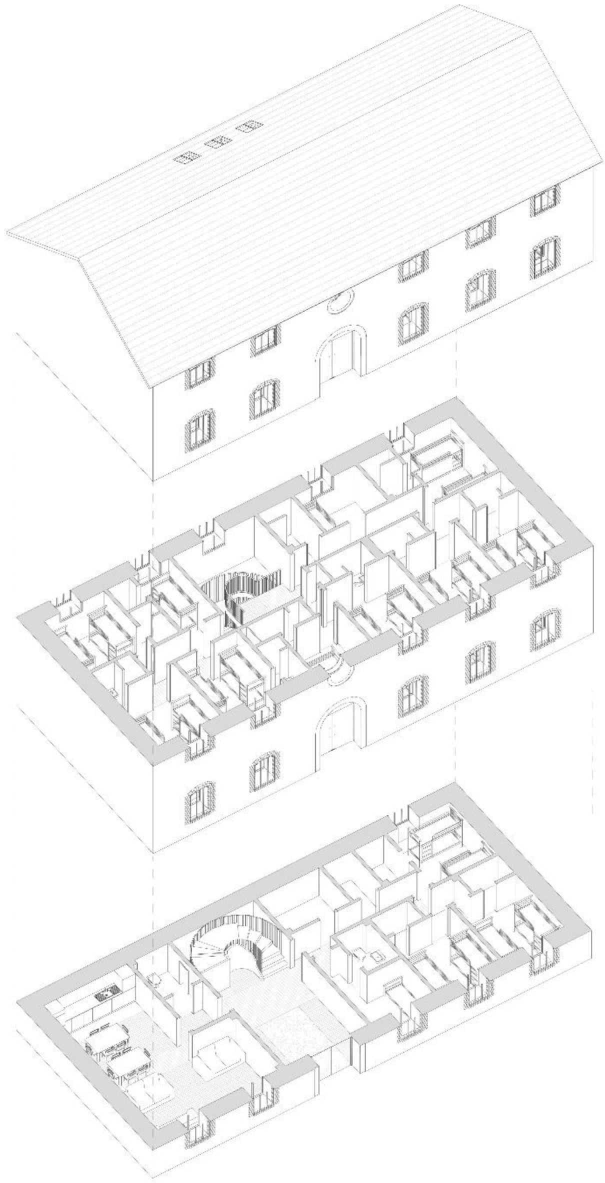

**Figure 5.5 –** Case Study 2 – The Barrel Store (Passvihaus Trust 2018)

In addition to an initial assessment of the condition of the structure, owing to concern regarding moisture accumulation, mould and fabric decay at the interface between the existing solid stone walls and the IWI, WUFI was utilised to complete a moisture risk assessment. Principally given the original design intent to ensure EnerPHit accreditation, THERM was equally used to minimise thermal bridging at those deemed complex junctions with PHPP being used to model the overall structure, again, ensuring accordance with the EnerPHit certification criteria (Greengauge [no date]).

**Figure 5.6 –** Case Study 2 – The Barrel Store (Passvihaus Trust 2018)

## 6.0 Discussion

The presented case studies have permitted broad substantiation of the proposed assessment framework and process, with both case studies undertaking something akin to the retrofit survey, WUFI modelling to appreciate moisture risk and an overheating assessment – facilitated by PHPP within the case studies as opposed to the initial use of the Good Homes Alliance early stage overheating risk tool.

It is however recognised that the initial assessment completed in both case studies does not appear to extend to the detail proposed by the retrofit survey, with a lack of explicit reference made to an analysis of services and occupants. However, despite this, these are still deemed fundamental considerations as a part of the retrofit survey in order to ensure a whole house assessment.

Equally, as with the discussion regarding THERM and the need to complete a detailed assessment of thermal bridges, the case study of Cumberworth and the use of VIPs to window and door reveals in the absence of any more detailed assessment substantiated the further hypothesis that a professional may deem it unnecessary to undertake detailed modelling of a particular aspect and instead rely on experience. Whilst it was accepted by Green Building Store that the use of this approach may have led to the introduction of unintended consequences, as previously highlighted by Smith (2017), it is equally accepted that there is no guaranteed way to fully design out risk and that, in the case of thermal bridging, experience and good detailing may prove sufficient.

As a result of the alignment of the methodology used within the case studies with that of the proposed assessment process, and despite the aforementioned minor variations with respect to the retrofit survey and detailed analysis of thermal bridging, the proposed process remains unaltered.

## 7.0 Conclusion and Further Research

As we have seen, the successful retrofit of any building is complex, with this complexity being amplified in the case of traditional buildings as a result of their inherent complexity and their potential evolution over a period of time to consist of a combination of old, new and potentially unsuitable materials; the heterogenous nature of materials involved in their original construction; their external environment; their occupants; and, crucially, the complex interrelationship of the physical properties of moisture, ventilation and heat, and an alteration of these properties and a dynamic equilibrium that will have been organically attained to ensure the healthy function of the building.

Whilst this complexity exists and is widely acknowledged, we have equally seen the opportunity that exists to retrofit the traditional building stock, the Government policy and drivers, and our underlying obligation to the planet and future generations to enhance this building stock to increase efficiencies and reduce carbon emissions. As such, the retrofit of traditional buildings is inevitable and we must therefore look to manage the risks associated with the retrofit of this building stock and the avoidance of the introduction of unintended consequences which may lead to fabric decay and detrimental impacts to occupant health.

As we have taken each unintended consequence in-turn – explicitly that of moisture penetration, condensation, interstitial condensation, thermal bridging, overheating and indoor air quality – and despite the recognised restrictions of various methodologies and the cost, complexity and time incurred, we have been able to devise a framework and process with which to initially complete a whole house assessment of context, fabric, condition, occupants and services – the retrofit survey – and supplement this with additional detailed modelling so as to derive a clear, sufficiently detailed, sequential assessment process for the energy retrofit of small-scale domestic traditional buildings.

Whilst we have bounded the assessment process to ensure it remains feasible within the context of a typical domestic retrofit, there remains a concern of whether homeowners would be willing to remunerate professionals for the time taken to adequately analyse a building prior to determining the most appropriate form of intervention and whether it may be more probable that, whilst the process has been bounded, going to these lengths is prohibitively expensive for the homeowner with the likely consequence that either: a. those not adequately qualified undertake an analysis; b. the professional is expected to utilise experience to determine the intervention and therefore expose themselves, the owner, and building to risk; or c. no form of analysis is completed in the first instance. Whatever the outcome, as we have seen, it is sensible to take a cautionary approach and therefore, if the client is not willing to pay for assessment and adherence to the process, then it may be sensible to decline the commission, as opposed to taking on undue risk.

Following development of the framework and process, the equal logical next step is to trial its function, validating it remains feasible within the context of a typical domestic retrofit, whilst equally ensuring sufficiently detailed assessment is undertaken to allow mitigation of risk and the designing out of unintended consequences.

There are a range of aspects warranting further consideration in the potential development of this thesis with it being clearly recognised that, whilst not the original intent, the devised process ignores the equal crucial heritage aspects, such as the significance of the structure, which must be factored in during a broader assessment process to permit the correct design solution. A range of relevant other considerations exist, which would equally form a natural development of this thesis and allow consideration of additional aspects such as economics and lifecycle operating costs; embodied carbon; the level of disruption for the homeowner; a more detailed consideration of indoor air quality and impacts to occupant health; and, the increasing impacts of climate change to the external environment and the allowances for this in any assessment so as to adequately inform the design solution.

# 8.0 Appendix

## 8.1 Appendix A – Summary list of the 19 most common unintended consequences of installing SWI (King 2016)

| Unintended consequence | Cause |
|---|---|
| Overheating (increases in temperature above 28° in the summer months) | Observed through both modelling and in the field. It is recognised that overheating can be a problem in all dwellings which have received solid wall insulation. This is particularly a problem for (but not restricted to) those that have been treated with internal wall insulation as a result of decoupling of thermal mass from the dwelling. |
| Increased relative humidity, and associated damp and mould growth | As a result of increasing airtightness (not correctly alleviated e.g. through extract fans), increases in internal humidity can occur. This can lead to damp problems, and mould growth, with associated health problems for the occupants. The problem can be particularly associated with un-treated thermal bridges within dwellings. |
| Negative effect on neighbouring dwellings. | There is the potential for the installation of solid wall insulation on one property to affect neighbouring dwellings. This is because the relative temperatures of the walls of the dwellings will be adjusted. As a result, moisture can condense on a neighbouring property in a place where it did not previously cause damp, mould and other problems. |
| Shifting of thermal bridging to new points | The application of solid wall insulation can affect the internal condensation points. This can create new points which are incapable of withstanding exposure to condensation. |
| Increased risk of dry or wet rot to timbers. | The risk of dry rot developing increases with increased levels of humidity which can occur following the installation of solid wall insulation. An increase in wet rot can be caused by high levels of moisture or humidity in timbers due to poor detailing. |
| Increase risk of insect attack on timbers | Insect attack to timber structures is increased if the timbers are not kept dry. In older solid wall dwellings (where timbers are more prevalent) any increase in the relative humidity can lead to an increased risk of insect attack on timbers. |
| Increased risk of dust mites, bed bugs, clothes moths and other insects within the home | A number of household pests including dust mites, bed bugs and clothes moths are more active and prevalent in increased humidity which can follow the installation of solid wall insulation. |
| Increased Radon risk | In areas of the country prone to Radon (e.g. areas of South West England) increasing airtightness following the installation of solid wall insulation could potentially result in an increase in the risk of exposure to occupants. |
| Rot of internal floor and roof timbers | With internal insulation floor and roof joists can become significant thermal bridges unless particular care is taken. Due to increases in humidity, these thermal bridges can then rot as moisture condenses on them, causing significant structural problems. |
| Damage to the external wall structure, or failure of internal finishes, due to water fill and frost damage following internal insulation | The application of internal wall insulation can mean that an external wall is no longer dried by heating the interior of the dwelling. As a result, moisture is not driven out of the walls, which can cause structural damage and the failure and decoupling of the internal finishes (including the internal insulation itself). One mechanism for damage is 'frost damage' to the brick as the water in the wall freezes. |

| | |
|---|---|
| | It is important to understand the physics of how solid walls perform and deal with moisture transference based on their levels of humidity. |
| Increased interstitial condensation | An increase in humidity can result from the application of solid wall insulation, leading to condensation in interstitial spaces (such as in roof eaves etc.), or within the structure of the walls. In addition, moisture trapped in walls by closed cell insulation can result in moisture migration to the inner surfaces of the building, resulting in mould and premature decay of finishes and fittings. |
| Short-term reduction in air quality following installation of solid wall insulation (Formaldehyde and other VOCs) | There is a risk of increased levels of toxic volatile organic compounds (VOCs) including formaldehyde from the adhesives and other substances used in insulation products. These substances can have significant short and long-term effects on the health of occupants, with many being carcinogenic. |
| Long-term reduction in air quality following solid wall insulation (CO, $CO^2$ levels) | A reduction in air quality over the longer term as a result of reduced levels of ventilation following solid wall insulation may occur. This may lead to increases of Carbon Monoxide and Carbon Dioxide, both of which can have short- and long-term effects on physical and mental health of occupants. |
| Aesthetics | From a cultural or aesthetic point of view, the use of external wall insulation may have a significant impact on the character and vernacular of many towns and cities throughout the UK. |
| Property value | The effect of solid wall insulation on property value is uncertain. While some value can be assigned to the lower levels of energy consumption, lower values may result from any reduction in aesthetic appeal, or reduction in internal space resulting from the works. |
| Daylighting | Research undertaken by BRE indicates that the use of wall insulation can have a detrimental effect of internal day light factors. This has a counter factual outcome of providing insulation to reduced energy demand, with the potential for increased energy demand on lighting, and less benefit from solar gain. |
| Durability and maintenance and repair consequences | Solid walls with no insulation applied either internally or externally are very robust and sturdy structures. The introduction of materials that are effectively air traps and less resilient to impact could potentially have an unintended consequence of an increased demand for maintenance and repair, as a result of damage or even normal usage. |
| Disturbance | The installation of solid wall insulation has the potential for disturbing not only the occupiers but also the surrounding vicinity, with the erection of scaffolding, deliveries and other incidental activities. As a consequence, when residents understand the extent of disturbance, it may become a disincentive to having the improvement works undertaken. |
| Fire safety | Applying solid wall insulation internally or externally may introduce a potential for increased fire risk to buildings, unless this consequence is fully considered. There are potentially significant risks of creating a fire bridge between dwellings with external wall insulation systems over several dwellings (e.g. a block of flats). |

## 8.2 Appendix B – Retrofit Survey | Pro-Forma (Author's own 2019)

### RETROFIT SURVEY DETAILS

| | |
|---|---|
| Surveyor's Name: | |
| Date of Inspection: | |
| Time of Inspection | Start: _________________ Finish: __________________ |
| Weather Conditions: | Hot / Mild / Cold Dry / Overcast / Rain / Snow<br>*Comments:* |
| Weather in Preceding Period: | Hot / Mild / Cold Dry / Overcast / Rain / Snow<br>*Comments:* |

## PROPERTY & CONSTRUCTION DETAILS

| | |
|---|---|
| Full Property Address: | |
| Property Type: | House Detached · Bungalow Semi-Detached · Chalet Terraced · Flat End-Terrace · Maisonette Enc. Terrace · Other |
| Est. Date Construction: *(describe evidence)* | |
| Est. Date Extension(s): *(describe evidence)* | |
| Broad overview of construction and materials *(includes aspects such as permeability)* | |

## ACCOMMODATION

| Floor | Living Rooms | Beds | Bath / Shower | Separate Toilet | Kitchen | Utility Room | Conservatory | Other | Name of Other |
|---|---|---|---|---|---|---|---|---|---|
| Lower Ground | | | | | | | | | |
| Ground | | | | | | | | | |
| First | | | | | | | | | |
| Second | | | | | | | | | |
| Third | | | | | | | | | |
| Other | | | | | | | | | |
| Roof Space | | | | | | | | | |

| | |
|---|---|
| Site Features: | Flood Risk Zone: Flood Zone 1 / Flood Zone 2 / Flood Zone 3<br>Radon Risk (ukradon): < 1% / 1 – 3% / 3 - 5% / 5 – 10% / 10 – 30% / > 30%<br>Exposure Zone (BRE 262): Zone 1 / Zone 2 / Zone 3 / Zone 4<br>Exposure Comments:<br><br>Trees:<br><br>Shading:<br><br>*Other General Comments (e.g. adjoining structures, walls, hedging, etc.)* |
| Block Plan Sketch:<br>*(including orientation)* | |

## PEOPLE

| | |
|---|---|
| Ownership Status: | Owner Occupied / Tenanted / Vacant<br><br>Tenure:<br><br>*General Comments:* |
| Number Occupants:<br>(typically) | 1 2 3 4 5+ |
| Occupation Pattern:<br>*Relevant commentary regarding typical occupation patterns* | |
| Behaviour:<br>*Relevant commentary regarding use of building, e.g.*<br>*- Internal drying of clothes*<br>*- Operation of heating* | |

| | |
|---|---|
| Mains Services & Renewables: | Drainage Gas Electricity Water<br>*Other (e.g. PV, Solar Thermal, GSHP, ASHP, Biomass):* |
| Central Heating: | Gas (mains) Gas (LPG) Electricity Solid Fuel Oil<br>None *Other (describe):* |
| Central Heating Controls: | Boiler Wired Thermostat Wireless Thermostat Smart Thermostat<br>*Other:* |
| Central Heating Output Type: | UFH Wet Emitters Electric Emitters TRVs<br>*Other/Comments* |
| Central Heating Function:<br>*functioning during inspection & operating as expected?* | |
| DHW: | Gas (mains) Gas (LPG) Electricity Solid Fuel Oil<br>None *Other (describe):* |
| DHW Function:<br>*functional during inspection & operating as expected?* | |
| Fireplaces / Stoves: | |
| General: | |

## SERVICES | VENTILATION

| | |
|---|---|
| Ventilation Strategy | Passive Stack Intermittent Extract Mechanical Extract Positive Input<br>MVHR<br>*Other/Comments:* |
| Draughtproofing | Doors<br>Present? Yes / No<br>Windows<br>Present? Yes / No<br>*Comments:* |
| Trickle Vents | Doors<br>Present? Yes / No<br>Open During Inspection? Yes / No<br>Windows<br>Present? Yes / No<br>Open During Inspection? Yes / No<br>*Comments:* |

## MECHANICAL EXTRACT LOCATION, NUMBER, TYPE (TIMED/SWITCHED/HUMIDISTAT), FUNCTIONAL?

| Floor | Living Rooms | Beds | Bath / Shower | Separate Toilet | Kitchen | Utility Room | Conservatory | Other | Name of Other |
|---|---|---|---|---|---|---|---|---|---|
| Lower Ground | | | | | | | | | |
| Ground | | | | | | | | | |
| First | | | | | | | | | |
| Second | | | | | | | | | |
| Third | | | | | | | | | |
| Other | | | | | | | | | |
| Roof Space | | | | | | | | | |

*Comments:*

## FABRIC | ROOF SPACES | NOTES

| Considerations | Notes | Key Points |
|---|---|---|
| *Structural*<br>*Ventilation*<br>*Insulation* | | |

*ADDITIONAL NOTES OVERLEAF IF REQUIRED….*

## ROOF SPACES | ACTION POINTS

| | | |
|---|---|---|
| Insulation? | Underfelting? | Ventilation? |
| Lag pipes / Tanks? | Strengthen Timbers? | Ceilings? |
| Chimney Breast Support? | Party Walls Fire Stopped? | Rot or Beetle? |
| *Other Specific Comments:* | | |

## ROOF SPACES | INSPECTION LIMITATIONS & OTHER

| | | | |
|---|---|---|---|
| Access Hatch? | Decking? | Insulation? | Contents? |
| Safety of Pull Down Ladder? | | | |

## Fabric | Second Floor | Notes

| Considerations | Notes | Key Points |
|---|---|---|
| *Ceilings: Plasterboard, Lath & Plaster, Concrete Slab*<br>*Outer walls (solid/cavity)*<br>*Partitions*<br>*Floors (solid/timber)*<br>*Floors (type, e.g. Posi?)*<br>*Floors (embedded in wall?)*<br>*Floors (firm – joist depth)*<br>*Windows*<br>*Doors*<br>*Chimneys*<br>*Floor Coverings* | | |

*ADDITIONAL NOTES OVERLEAF IF REQUIRED….*

## Second Floor | Action Points

| Doors? | Windows? | Movement? |
|---|---|---|
| *Other Specific Comments:* | | |

## Second Floor | Inspection Limitations & Other

| Floors Covered | Furniture |
|---|---|
| *Other Specific Comments:* | |

## FABRIC | FIRST FLOOR | NOTES

| Considerations | Notes | Key Points |
|---|---|---|
| *Ceilings: Plasterboard, Lath & Plaster, Concrete Slab*<br>*Outer walls (solid/cavity)*<br>*Partitions*<br>*Floors (solid/timber)*<br>*Floors (type, e.g. Posi?)*<br>*Floors (embedded in wall?)*<br>*Floors (firm – joist depth)*<br>*Windows*<br>*Doors*<br>*Chimneys*<br>*Floor Coverings* | | |

*ADDITIONAL NOTES OVERLEAF IF REQUIRED….*

## FIRST FLOOR | ACTION POINTS

| Doors? | Windows? | Movement? |
|---|---|---|
| *Other Specific Comments:* | | |

## FIRST FLOOR | INSPECTION LIMITATIONS & OTHER

| Floors Covered | Furniture |
|---|---|
| *Other Specific Comments:* | |

## FABRIC | GROUND FLOOR | NOTES

| Considerations | Notes | Key Points |
|---|---|---|
| *Ceilings: Plasterboard, Lath & Plaster, Concrete Slab*<br>*Outer walls (solid/cavity)*<br>*Partitions*<br>*Floors (solid/timber)*<br>*Floors (type, e.g. Posi?)*<br>*Floors (embedded in wall?)*<br>*Floors (firm – joist depth)*<br>*Windows*<br>*Doors*<br>*Chimneys*<br>*Floor Coverings*<br>*Floor Insulation* | | |

*ADDITIONAL NOTES OVERLEAF IF REQUIRED….*

## GROUND FLOOR | ACTION POINTS

| Doors? | Windows? | Movement? |
|---|---|---|
| *Other Specific Comments:* | | |

## GROUND FLOOR | INSPECTION LIMITATIONS & OTHER

| Floors Covered | Furniture |
|---|---|
| *Other Specific Comments:* | |

## FABRIC | DAMP, TIMBER, HAZARDOUS MATERIALS

| Considerations | Notes | Key Points |
|---|---|---|
| *DPC (plastic/bituminous/ felt/slate/other)*<br>*Recent work/drillings?*<br>*Sub-floor ventilation*<br>*DPC 150mm clearance*<br>*DPC bridged*<br>*Gutter splash etc.*<br>*DPM*<br>*Condensation*<br>*Mould*<br>*Wood boring beetle*<br>*Wet rot*<br>*Dry rot* | | |

*ADDITIONAL NOTES OVERLEAF IF REQUIRED….*

## DAMP, TIMBER, HAZARDOUS MATERIALS | ACTION POINTS

| Sub-floor ventilation | DPC? | Damp? |
|---|---|---|
| *Other Specific Comments:* | | |

## FABRIC | EXTERIOR ELEVATIONS | NOTES

| Considerations | Notes | Key Points |
|---|---|---|
| *Chimneys*<br>*Flashings / soakers*<br>*Roof covering*<br>*Parapets / valleys*<br>*Eaves*<br>*Gutters*<br>*Rain water pipes*<br>*Walls*<br>*DPC*<br>*Woodwork*<br>*Extensions*<br>*Movement*<br>*Double glazing* | | |

*ADDITIONAL NOTES OVERLEAF IF REQUIRED....*

## EXTERIOR ELEVATIONS | ACTION POINTS

| | | |
|---|---|---|
| Pointing / Rendering? | Woodwork / Redecoration? | Rain Water Goods? |
| Roof? | Stacks? | Movement? Engineer? |
| *Other Specific Comments:* | | |

## EXTERIOR ELEVATIONS | INSPECTION LIMITATIONS & OTHER

| | | | |
|---|---|---|---|
| Roof areas not visible? | Ivy/climber on walls? | Flat roofs/parapets not seen? | Adjoining gardens/non-public areas not entered |
| *Other Specific Comments:* | | | |

## RETROFIT SPECIFIC CONSIDERATIONS

| | |
|---|---|
| Electricity Box Location: | |
| Gas Meter Location: | |
| Stop Cock Location: | |
| External Perforations & Fixings: | |
| Eaves Detailing & Overhang: | |
| Furnishing Status: | Furnished / Part Furnished / Empty / Derelict / Overgrown<br><br>*Comments:* |
| Internal Fixtures & Fittings: | |
| Window Reveal Depth: | |
| Door Reveal Depth: | |

## 8.3 Appendix C - Early Stage Overheating Risk Tool (Good Homes Alliance 2019b)

# EARLY STAGE OVERHEATING RISK TOOL

Version 1.0, July 2019

This tool provides guidance on how to assess overheating risk in residential schemes at the early stages of design. It is specifically a pre-detail design assessment intended to help identify factors that could contribute to or mitigate the likelihood of overheating.

The questions can be answered for an overall scheme or for individual units. Score zero wherever the question does not apply. Additional information is provided in the accompanying guidance, with examples of scoring and advice on next steps.

Find out more information and download accompanying guidance at goodhomes.org.uk/overheating-in-new-homes

Good Homes Alliance

**KEY FACTORS INCREASING THE LIKELIHOOD OF OVERHEATING** | **KEY FACTORS REDUCING THE LIKELIHOOD OF OVERHEATING**

### Geographical and local context

| | | |
|---|---|---|
| **#1 Where is the scheme in the UK?** See guidance for map | South east | 4 |
| | Northern England, Scotland & NI | 0 |
| | Rest of England and Wales | 2 |
| **#2 Is the site likely to see an Urban Heat Island effect?** See guidance for details | Central London (see guidance) | 3 |
| | Grtr London, Manchester, B'ham | 2 |
| | Other cities, towns & dense sub-urban areas | 1 |

| | |
|---|---|
| **#8 Do the site surroundings feature significant blue/green infrastructure?** Proximity to green spaces and large water bodies has beneficial effects on local temperatures; as guidance, this would require at least 50% of surroundings within a 100m radius to be blue/green, or a rural context | 1 |

### Site characteristics

| | | |
|---|---|---|
| **#3 Does the site have barriers to windows opening?** - Noise/Acoustic risks - Poor air quality/smells e.g. near factory or car park or very busy road - Security risks/crime - Adjacent to heat rejection plant | Day - reasons to keep all windows closed | 8 |
| | Day - barriers some of the time, or for some windows e.g. on quiet side | 4 |
| | Night - reasons to keep all windows closed | 8 |
| | Night - bedroom windows OK to open, but other windows are likely to stay closed | 4 |

| | |
|---|---|
| **#9 Are immediate surrounding surfaces in majority pale in colour, or blue/green?** Lighter surfaces reflect more heat and absorb less so their temperatures remain lower; consider horizontal and vertical surfaces within 10m of the scheme | 1 |
| **#10 Does the site have existing tall trees or buildings that will shade solar-exposed glazed areas?** Shading onto east, south and west facing areas can reduce solar gains, but may also reduce daylight levels | 1 |

### Scheme characteristics and dwelling design

| | |
|---|---|
| **#4 Are the dwellings flats?** Flats often combine a number of factors contributing to overheating risk e.g. dwelling size, heat gains from surrounding areas; other dense and enclosed dwellings may be similarly affected - see guidance for examples | 3 |
| **#5 Does the scheme have community heating?** i.e. with hot pipework operating during summer, especially in internal areas, leading to heat gains and higher temperatures | 3 |

| | | |
|---|---|---|
| **#11 Do dwellings have high exposed thermal mass AND a means for secure and quiet night ventilation?** Thermal mass can help slow down temperature rises, but it can also cause properties to be slower to cool, so needs to be used with care - see guidance | | 1 |
| **#12 Do floor-to-ceiling heights allow ceiling fans, now or in the future?** Higher ceilings increase stratification and air movement, and offer the potential for ceiling fans | >2.8m and fan installed | 2 |
| | > 2.8m | 1 |

### Solar heat gains and ventilation

| | | |
|---|---|---|
| **#6 What is the estimated average glazing ratio for the dwellings?** (as a proportion of the facade on solar-exposed areas i.e. orientations facing east, south, west, and anything in between). Higher proportions of glazing allow higher heat gains into the space | >65% | 12 |
| | >50% | 7 |
| | >35% | 4 |
| **#7 Are the dwellings single aspect?** Single aspect dwellings have all openings on the same facade. This reduces the potential for ventilation | Single-aspect | 3 |
| | Dual aspect | 0 |

| | | Full | Part |
|---|---|---|---|
| **#13 Is there useful external shading?** Shading should apply to solar exposed (E/S/W) glazing. It may include shading devices, balconies above, facade articulation etc. See guidance on "full" and "part". Scoring depends on glazing proportions as per #6 | >65% | 6 | 3 |
| | >50% | 4 | 2 |
| | >35% | 2 | 1 |

| | | Openings compared to Part F purge rates: = Part F | +50% | +100% |
|---|---|---|---|---|
| **#14 Do windows & openings support effective ventilation?** Larger, effective and secure openings will help dissipate heat - see guidance | Single-aspect | minimum required | 3 | 4 |
| | Dual aspect | minimum required | 2 | 3 |

**TOTAL SCORE** [ ] = Sum of contributing factors: [ ] *minus* Sum of mitigating factors: [ ]

High — 12 — Medium — 8 — Low

| score >12: | score between 8 and 12: | score <8: |
|---|---|---|
| Incorporate design changes to reduce risk factors and increase mitigation factors AND Carry out a detailed assessment (e.g. dynamic modelling against CIBSE TM59) | Seek design changes to reduce risk factors and/or increase mitigation factors AND Carry out a detailed assessment (e.g. dynamic modelling against CIBSE TM59) | Ensure the mitigating measures are retained, and that risk factors do not increase (e.g. in planning conditions) |

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