Ministry of Housing,
Communities &
Local Government

Research into resistance to moisture in buildings

Using numerical simulation to assess moisture risk in retrofit constructions. Part 2

July 2019
PRP Architects LLP
Ministry of Housing, Communities and Local Government

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July 2019

The document is prepared by Innovate at PRP Limited, part of PRP Architects LLP.

Contents

1. Background

It is a requirement of Part C of the Building Regulations that buildings, and people who use these buildings, are adequately protected from harmful effects of moisture. Approved Document C provides guidance on how to meet this requirement. However, much of this guidance was made before the energy performance requirements for buildings were improved in recent years and it is not certain that these recommendations are still appropriate. In addition, Approved Document C refers to a number of British Standards and other publications, but the usefulness and applicability of these documents, particularly in relation to retrofit works, required reviewing. It should be noted that this project focused specifically on moisture from precipitation, surface and interstitial condensation.

The Ministry of Housing, Communities and Local Government (MHCLG) commissioned PRP to carry out this research study, entitled *Research into resistance to moisture in buildings.*

The project was delivered in three main stages:

- **Stage One: Background research**
  Stage One covered all the background research activities required to inform the refinement of the analysis methodology and the parameters used for the analysis.

- **Stage Two: Detailed analysis of identified construction typologies**
  Stage Two involved the detailed analysis of the various construction types identified in Stage One for both new build and retrofit, including key thermal bridge junctions. In this stage, a number of software analysis packages and methodologies will be used to carry out a sensitivity analysis on each of the identified construction typologies:

  - Simplified Modelling based on *BS EN ISO 13788 (2012)* - the 'Glaser Method'
  - Standardised Modelling based on *BS EN 15026 (2007)* - with the use of a software package, WUFI (Wärme und Feuchte Instationär)
  - Multi-dimensional Thermal Modelling to *BS EN ISO 10211 (2007)* - with the use of THERM (for construction junctions only)

- **Stage Three: Simplified rules and recommendations**
  Stage Three involved the formulation of simplified rules and recommendations using the conclusions from the Stage Two work.

The outputs of this research are a series of eight reports, entitled:

- Research into resistance to moisture in buildings: Research Summary
- Research into resistance to moisture in buildings: Identification of common types of construction.
- Research into resistance to moisture in buildings: Using calculation methods to assess surface and interstitial condensation

- Research into resistance to moisture in buildings: Using numerical simulation to assess moisture risk in new constructions
- Research into resistance to moisture in buildings: Using numerical simulation to assess moisture risk in retrofit constructions. Part 1
- **Research into resistance to moisture in buildings: Using numerical simulation to assess moisture risk in retrofit constructions. Part 2**
- Research into resistance to moisture in buildings: Assessment of current moisture guidance
- Research into resistance to moisture in buildings: Simplified rules for reducing the risk of moisture

2. Moisture Assessment Methods and Risk Criteria

This report is the **Using numerical simulation to assess moisture risk in retrofit constructions. Part 2** report of the Research into resistance to moisture in buildings project.

The **Using numerical simulation to assess moisture risk in retrofit constructions. Part 1** report highlighted that build-ups retrofitted with internal wall insulation (IWI) tended to be risky build-ups, displaying poor hygrothermal performance. Therefore this additional research has investigate these specific build-ups, with typical vapour-open insulation materials being retrofitted, rather than typical vapour-closed insulation materials used in the Part 1 retrofit report.

2.1. Hazards associated with moisture risks in buildings

The presence of excess moisture can lead to health issues for occupants and damage to building fabric, and can cause the following problems:

- <u>Mould Growth</u>
  High internal relative humidity (RH) levels are favourable to surface mould growth and dust mites.

- <u>Condensation</u>
  Excess moisture can lead to both surface and interstitial condensation, which can lead to building fabric damage if organic or 'fragile' material (a material that degrades in the present of moisture, e.g. timber) is present.

- <u>Damage due to high moisture content in materials</u>
  Such conditions can promote rot in ‘fragile’ material (e.g. timber), which can lead to failure of building fabric elements including structural elements.

- <u>Reduced performance of insulating materials</u>
  High moisture content (from 80% of relative humidity levels, up to 100% where condensation occurs) can have a detrimental effect on the thermal performance of the material, as most insulation materials have a moisture-dependent thermal conductivity. Generally speaking, very high levels of moisture in insulation materials tend to lead to a significantly poorer thermal conductivity.

- <u>Frost damage</u>
  When excess moisture is held in its liquid form in external surfaces of solid masonry walls, it will freeze in very cold conditions and cause damage to the masonry, particularly brickwork.

- <u>Corrosion</u>
  Corrosion of metallic compounds that are in contact with, or buried within, the

wall. Corrosion occurs due to the presence of surface condensation on these compounds.

2.2. Assessment Methods

Currently the main guidance for moisture risk assessment standards in the UK are British Standard BS 5250 (2011): *'Code of practice for control of condensation in buildings'* and a standardised modelling method BS EN ISO 13788 (2012): *'Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods'*. These standards are useful in particular situations to provide an accurate moisture risk assessment. However, under certain conditions (described in paragraph 3.2.2), the limitations of these standards mean that currently they cannot provide a robust moisture risk assessment and cannot be relied on. This is where further modelling methods, such as BS EN 15026 (2007): *'Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation'*, are introduced.

It is therefore important to identify whether existing standards can be used with confidence to assess moisture risk and which construction typologies these standards are applicable to. Where existing standards can be seen to be insufficient it is important to clarify whether these standards need to be combined with other methodologies and form part of an expanded assessment.

Four different assessment methods currently exist in the industry, as explained in the Moisture Risk Assessment and Guidance document by Sustainable Traditional Buildings Alliance (STBA) and Department of Energy & Climate Change (DECC) (2014) and summarised in the sub-sections below. The four different assessment methods can be regarded as a hierarchy of assessment; each assessment method has an increased complexity that requires more complex input data as well as a more in-depth understanding of the subject matter in order to carry out the assessment.

The choice of assessment method for each construction typology is explained within their respective results section. As the M7A report focuses on risky build-ups, the main risk assessment methods used in this additional report are BS 5250 (2011) for guidance and BS EN 15026 (2007) for an assessment method adequate to the nature of the modelled build-ups.

2.2.1. Prescriptive Guidance BS 5250 (2011)

Prescriptive guidance is based on experience and details the commonly used applications for which there is good evidence of success over many years. BS 5250 (2011) is mainly based on prescriptive guidance.

2.2.2. Simplified Modelling to BS EN ISO 13788 (2012) (the 'Glaser Method')

The assessment method BS EN ISO 13788 (2012) is a one-dimensional steady-state assessment method predicting the risk of surface and interstitial condensation through a multi-layered structure occurring under specified environmental (monthly mean) conditions. This method only takes into account moisture transport via vapour diffusion alone.

The method has substantial limitations, such as the fact that it does not take into account any storage of moisture within the elements, or that the materials transport properties are not affected by moisture content. This means that an accurate moisture risk assessment will be limited to the build-ups where these aforementioned effects are considered negligible.

2.2.3. Standardised Modelling to BS EN 15026 (2007)

The BS EN 15026 (2007) assessment method is a one-dimensional transient modelling of heat and moisture flows through a multi-layered structure with complex transport properties. This method takes into account the heat and moisture storage, the latent heat affect, and any liquid and convective transport under realistic boundary and initial conditions (i.e. non-steady climate conditions both internally and externally).

Similarly to the BS EN ISO 13788 (2012) method, this method is limited to one-dimension assessment only and therefore junctions cannot be modelled. It also has some other limitations due to simplification around the modelling of air layers, as well as the lack of defined protocols and available data for materials, climate files, etc.

This assessment method is implemented in several software packages, including WUFI (Wärme und Feuchte Instationär), which is the software the most commonly used in the industry, and the one used for this stage of our research study.

2.2.4. Multi-dimensional Thermal Modelling to BS EN ISO 10211 (2007)

None of the hygrothermal assessment methods listed above is multi-dimensional and therefore none of them is able to assess moisture risks at junctions between different construction typologies. Surface condensation typically appears around junctions between materials due to low surface temperatures caused by any discontinuity of in the insulation layer. These moisture problems, mainly arising around junctions between different building elements, are called ‘connective effects’.

It is important to assess these junctions because surface condensation is also one of the main moisture risks that could lead to health issues for occupants and fabric damage. The effect of extra heat losses appearing around junctions can also be analysed with multi-dimensional thermal calculations using the methods specified in BS EN ISO 10211 (2007): '*Thermal bridges in building construction - heat flows and surface temperatures - detailed calculations*'.

BS EN ISO 10211 (2007) also refers to *BS EN ISO 6946 (2007) Building components and building elements - Thermal resistance and thermal transmittance - Calculation method.* The parameters used in the multi-dimensional thermal modelling work follow the parameters listed in this standard.

2.3. Assessment risk criteria with transient hygrothermal modelling

Condensation risk criteria are clearly defined in BS EN ISO 13788 (2012). This assessment leads to a 'Pass / Fail' approach. This method models and calculates the amount of condensation or evaporation in a build-up on a monthly basis for each month of the year. The accumulated mass of condensed water over the twelve months is then compared to the total amount of evaporation during the year. The calculated amount of condensation presence within the build-up and its persistence are then analysed to check if there is any moisture accumulation, and consequently provide a 'Pass / Fail' status to the risk of condensation in the build-up.

However, there are no clear moisture risk assessment criteria (with moisture combining both liquid water and water vapour) with the use of BS EN 15026 (2007).

There is not a clear set of moisture risk assessment criteria agreed within the industry yet, especially as different build-ups, materials and applications will require different criteria. However, the Fraunhofer Institute offers some guidance criteria which can be used as general criteria. The following criteria are used for the analysis of this WUFI modelling work:

- <u>Moisture must not accumulate over time</u>
  This criteria is considered to be the most important one. Moisture content, i.e. water present in an element under its liquid or vapour form, must be able to dry out rather than accumulating within. If the moisture content in the building element keeps increasing (even slowly) without drying, then problems will arise sooner or later.

- <u>RH levels at critical junctions should only ever rise above 80% for short periods of time (i.e. less than a month) to ensure good drying</u>
  This criteria excludes any outer portion of wall directly affected by driving rain since it is outside. Although the outer layer gets wetter, it will also dry out more thoroughly because of its location.

- <u>RH levels should drop below 80% within the first six months of simulation</u>
  If it takes longer than the first six months of a WUFI simulation for RH levels to drop below 80% at the critical point of a build-up, the build-up is likely to be inadequate as constant high RH levels are likely to lead to moisture damage

WTA Technical Sheet 6-4 *Innendämmung nach WTA I: Planungsleitfaden* (WTA, 2009) which is referred to in Historic Environment Scotland Technical Paper 15 (2015) provides some circumstances for IWI where the 80% RH threshold can be relaxed to 95%[1]. These are:

- Use of vapour permeable insulation continuously adhered to the existing wall to completely avoid any air space at the interface

[1] Criteria not yet adopted in the industry, however can provide a useful output.

- Use of renders, rain-screens or impregnations that prevent driving rain ingress
- Normal internal moisture load
- Certain vapour permeability thresholds (unspecified threshold, however it is assumed to refer to the use of vapour permeable materials only)

Based on the above criteria, status of transient hygrothermal modelling cases are listed into three different categories in this report: ‘pass’, ‘risky’ or ‘fail’.

2.4. Visualisation of results from transient hygrothermal modelling

Several outputs are used in this report in order to analyse the thermal performance of modelled junctions, as well as the hygrothermal performance of the modelled build-ups. The visualised outputs are listed and detailed below:

2.4.1. Graphs: Relative Humidity Levels

As listed in the risk assessment criteria in section 2.3, the next step will be to analyse the RH levels within a build-up (typically at interfaces between different layers) in order to assess the risk of interstitial condensation. For each typology, RH levels at the ‘critical’ junction, i.e. the junction being the most at risk of interstitial condensation, will be analysed.

RH levels at this junction will be monitored and displayed in a time-based graph, an example is shown in Figure 1. The x-axis represents time (in this case the 5-year modelling period) and the y-axis represents the RH levels at the critical junction (in percentage). In addition, the constant 80% RH level limit is displayed as a continuous red line, while the relaxed 95% RH level limit is displayed as a dotted red line.

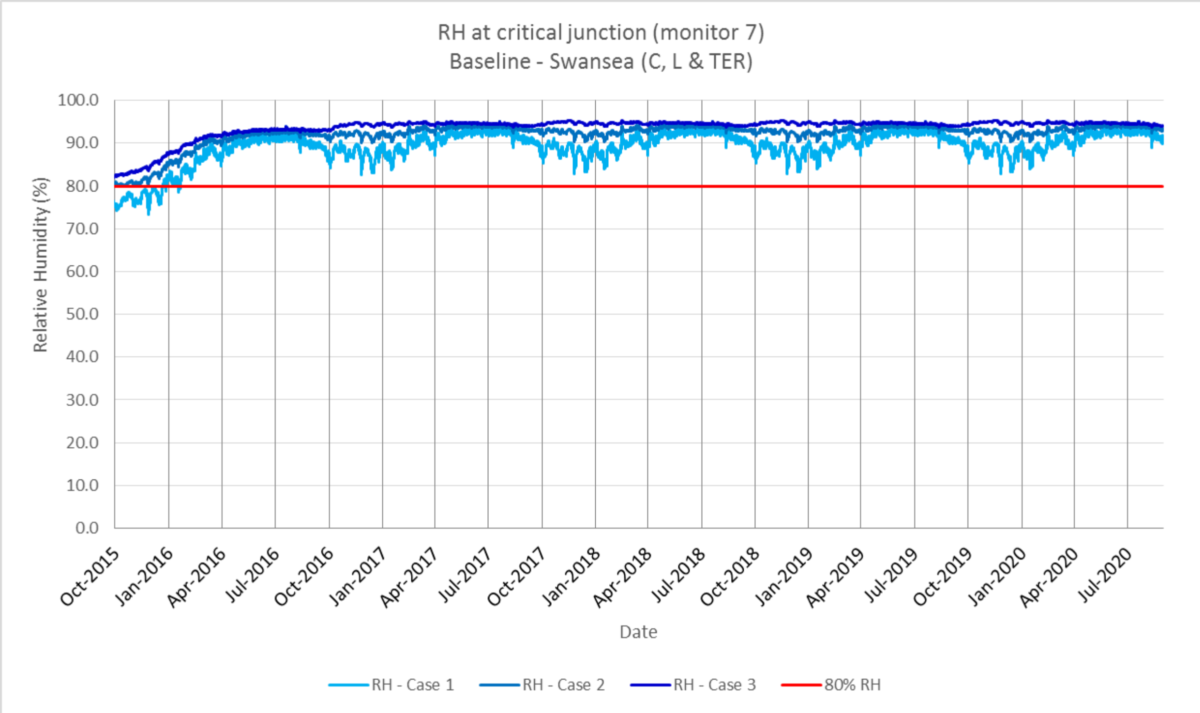


Figure 1: An example of an output graph for displaying RH at critical junction

3. WUFI Model Input Parameters

As the standardised method BS EN 15026 (2007) is a more recent assessment method and due to its lack of protocols (which adds some uncertainty to the results), all input data used commonly throughout all WUFI simulations in this research are listed in this section.

3.1. Materials

Physical properties of construction materials have a significant impact on the hygrothermal performance of a build-up. More specifically:

- porosity (w_{max})
- specific heat capacity (cp)
- thermal conductivity (λ)
- water vapour diffusion resistance factor (μ)
- moisture storage function, and suction & redistribution profiles (which are sometimes approximated in WUFI using the water absorption coefficient, called A-value)

There is currently a lack of tested / standardised material characteristics typically used in the UK construction industry. In the absence of such data, the material databases present in WUFI (Fraunhofer database, North-American database and others) are considered the best source of currently available data. Please refer to Appendix A for the exhaustive material list and their respective parameters used in the modelling.

3.2. Orientation, Inclination and Height

3.2.1. Orientation

Different parts of a building can be affected by very different micro-climates. In general, north-facing elevations can be subject to prolonged damp, as they are not exposed to the drying effect of the sun and they are usually sheltered from the drying effect of the wind. As a result, north façades tend to experience more stable conditions over time.

In contrast, fluctuations in temperature (due to solar radiations) and regular wetting and drying periods (due to the combined effects of wind, rain and solar radiations) means that south, west and south-west façades can suffer from accelerated rates of decay.

For this modelling work, the assumption is that the fluctuating conditions experienced on south-west façades are likely to be more detrimental to the hygrothermal performance of the build-up, compared to the constant damp experienced on north-facing façades. However, this assumption will not be true for all typologies as different typologies will be affected differently by these two different orientations. To analyse this, a sensitivity analysis with a change of orientation from south-west to north will be performed on specific typologies that could be particularly affected by constant damp related to a north-facing orientation.

All models (except explicitly stated) are oriented to face south-west, so as to model the most extreme scenario of wind-driven rain exposure and solar radiations. This is shown in section 3.5.1 – External Climate, displaying the characteristics of the weather files used, on which the wind-driven rain is the strongest from the south-west direction. The use of the south-west orientation is also the worst case for reverse diffusion due to this façade is experiencing the highest rate of solar radiations, which drives reverse diffusion in the summer.

3.2.2. Inclination

All wall models have an inclination of 90 degrees.

3.2.3. Height

All models have an assumed building height of less than 10m (described as low-rise buildings).

3.3. Surface Heat Transfer Coefficients

3.3.1. Surface Heat Transfer Coefficients

Surface heat transfer coefficients set in Table 1 below are used in the modelling, for unsheltered elements. They come from the calculation procedure set out in BS EN 15026 (2007) where possible, otherwise WUFI default settings are used.

Table 1: Surface Heat Transfer Coefficients

Heat flow direction	Horizontal
Rsi (internal)	0.131 m^2.K/W
Rse (external)	0.058 m^2.K/W

3.3.2. Adhering Fraction of Rain

Default values for adhering fraction of rain are used in the modelling.

- Adhering fraction of rain – Exposed wall = 70%
- Adhering fraction of rain – Protected build-up = 0%

3.4. Initial Conditions

3.4.1. Initial Moisture in Construction Typology

Initial moisture contents are taken in each layer of the build-up, set as typical built-in moisture content for each material, or with moisture content extracted from pre-retrofit equilibrium models (where applicable). This allows for appropriate built-in moisture levels in constructions using materials with significant built-in moisture at the time of construction (e.g. plasters).

3.4.2. Initial Temperature in Construction Typology

The initial temperature in the material layers is taken as 20°C, and is constant throughout the build-up. Even if this is not a realistic case for the simulations (starting 1st October), a constant initial temperature profile tends to be adequate for all of our modelling cases since the temperature distribution adapts to the prevailing boundary conditions within a few hours in the simulation (which extends for a 5-year period as a minimum).

3.5. Boundary Conditions

3.5.1. External Climate

Location, aspect and the differing exposure of individual elevations to direct sun and wind-driven rain influence the hygrothermal performance of the construction type.

The modelling work aims at providing an overall view of the performance of each typology. Therefore, four locations and associated external conditions, representative of the four main UK wind-driven rain exposure zones as represented in Diagram 12 of Approved Document C, are used in the modelling.

- Zone 1 – London
- Zone 2 – Manchester
- Zone 3 – Bristol
- Zone 4 – Swansea

Due to the lack of approved / standardised weather files to be used in WUFI, synthetic weather files for a ‘Design Reference Year’ are created, following the procedure in BS EN 15026 (2007), and used in the WUFI modelling work. The ‘Design Reference Year’ is constructed to cause the most severe conditions likely to occur once every ten years.

BS EN 15026 (2007) states that *‘a more severe climate is usually required when problems caused by moisture movement within structures are being investigated’* showing the need to use a ‘Design Reference Year’, instead of a ‘Typical Weather Year’ (generally based on long-term measured average data).

In terms of data on which the ‘Design Reference Year’ is based, it is worth noting that most cases in moisture movement problems require analysis in cold winter weather, however some moisture damage is worst in warm humid summer conditions (reverse condensation). Therefore, the ‘Design Reference Year’ is designed to combine low temperatures and solar radiation with high relative humidities, for climates where the winter situation is the most critical (as described in Annex B of BS EN 15026 (2007)).

Table 2 summarises the main characteristics of the four weather files used for this modelling work.

Table 2: Main characteristics of the four weather files used

	Exposure Zones			
	Swansea (Zone 4)	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Mean Temperature (°C)	10.5	11.3	10.3	12.1
Mean RH (%)	84.0	77.0	79.0	71.0
Counter-Radiation Sum (kWh/m^2.year)	2,829.0	2,828.0	2,781.0	2,825.0
Mean Cloud Index (%)	0.73	0.76	0.75	0.78
Mean Wind Speed (m/s)	5.89	4.73	4.18	3.97
Normal Rain Sum (mm/year)	795.0	610.0	596.0	543.0

The counter-radiation sum is the total of the atmospheric and terrestrial counter radiations over a period of a year. Both radiations are long-wave radiations and taken into account in the night time radiation cooling, which is especially important for roof build-ups.

See Figure 2 for a snapshot of the weather file analysis from WUFI for the most severe weather file Zone 4 – Swansea. Since no weather file was available for Swansea, the weather file from Pembrey Sands, which is the closest location to Swansea, was chosen for the modelling. It is a slight over-estimation as Pembrey Sands is to the west of Swansea and is slightly more exposed to wind and rain. This location highlights the dominance of south-west wind-driven rain, compared to other orientations.

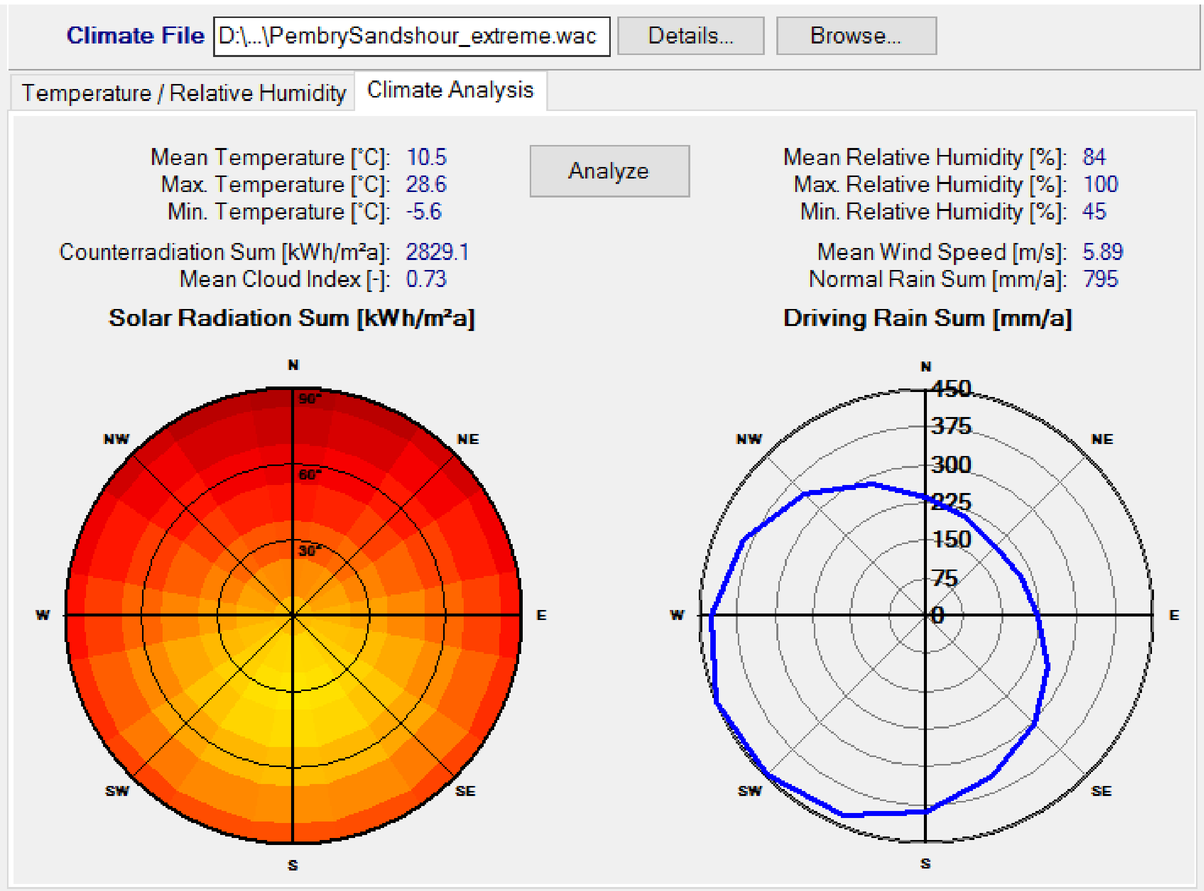


Figure 2: A snapshot of the weather file analysis from WUFI for the wind-driven rain exposure zone 4

This analysis from WUFI on the solar radiation sum is only comparative. The same colours on the solar radiation sum graphs are used for different weather files being analysed, but no legend is available to quantify solar radiations on different orientated façades. The software manual provides the following description: *'low values are displayed in dark red, medium values in yellow and high values in light blue'.*

3.5.2. Internal Moisture Conditions

Indoor conditions can play a significant role in the hygrothermal performance of a build-up. Indoor moisture loads are set in accordance to Annex C of BS EN 15026 (2007), where indoor conditions (temperature and relative humidity) are calculated based on external climate data (temperature). This simplified approach to determine indoor moisture conditions only applies to consistently heated buildings such as dwellings, residential buildings and schools.

For all models (except where explicitly stated in the sensitivity analysis), a 'normal' moisture load is used. This choice is made so as to analyse the hygrothermal performance of each typology without adding 'additional' stress due to poorer indoor conditions.

With the 'normal' moisture load condition, the indoor humidity is 30% for outdoor temperatures below -10°C, 60% for outdoor temperatures above 20°C and varying linearly with temperature for outdoor temperatures between these limits. With the ‘high’ moisture load condition, all humidity rates are 10% higher, i.e. varying linearly between 40% in winter (temperature less than -10°C) and 70% in summer (temperature greater than 20°C).

These two choices of indoor moisture condition are shown in Figure 3 and Figure 4:

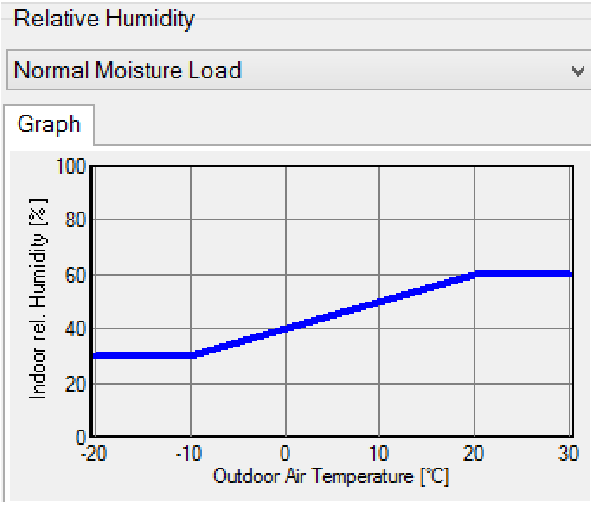


Figure 3: Normal moisture load

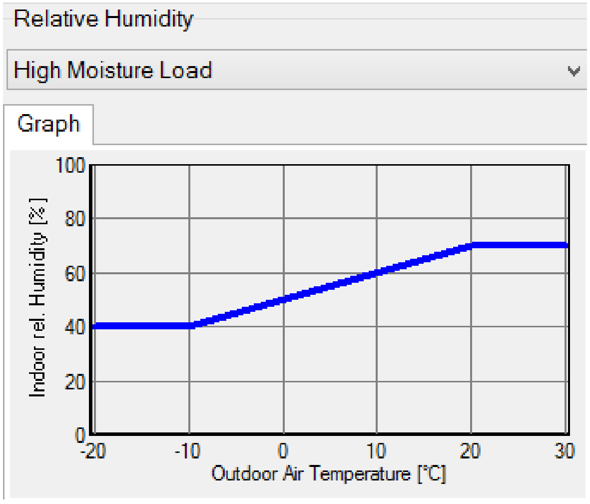


Figure 4: High moisture load

3.6. Other Modelling Parameters

All models are run for a simulation period of 5 years (or longer, should the construction type tested not reached equilibrium after 5 years), with a one-hour time increment and a start date of 1st October.

3.7. Modelling Limitations

For each simulation, a one-dimensional WUFI assessment includes the simulation of a specified build-up, using a location-specific climate file and includes assumptions on materials used (insulation, substrate and membranes), indoor conditions (moisture and temperature) and external conditions (moisture, temperature, rain, wind and solar radiations) for a set orientation and a set building height range.

These simulations are suitable for conditions where layers are not bridged, or where these bridging elements can be judged as insignificant hygrothermally.

However, there are a number of limitations worth noting:

- Build-ups
  the simulations are only considered representative of the main build-ups currently in the industry and cannot be extrapolated to cover every single possible build-up.

- Climate
  the climate files are generated from synthetic weather data. There is no agreed set of climate data ready for use with dynamic hygrothermal simulations in the UK currently.

- Standards
  While all the WUFI simulations and data analysis are carried out in accordance to BS EN 15026 (2007) and the STBA/DECC's guidance document, it is important to note that there are currently:
    - No protocols for use of BS EN 15026 (2007).
    - No protocols for non-standardised modelling to ASHRAE 160.
    - No protocols for non-standardised modelling for ABIS (As-built / In-service) conditions (as opposed to 'theoretical' conditions) and connective effects. Such modelling should aim to include effects like air leakage, thermal bypass, water ingress and other faults which could occur in practice.

- Two-dimensional modelling
  Two-dimensional simulation (which would be required to model junctions with 'sensitive' materials being present) is not included in this modelling work.

As such, any recommendations made as a result of modelling for this project can only be considered preliminary guidance as new protocols may vary from the approach taken here.

4. WUFI Modelling Scenarios

4.1. Baseline Scenario Variations

The baseline approach includes:

- Change in exposure zones (see Table 3)
- Change in build-up (i.e. insulation thickness) to meet target U-values as per M3 report (see Table 4)

Table 3: 12 cases as the baseline approach

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

Table 4: Target U-values

	U-value backstops ($W/m^2.K$)		
Construction Type	**Part C**	**Part L**	**TER**
Walls	0.70	0.35	0.18

Because each build-up is adjusted (using different insulation thicknesses) to match the target U-values listed above, the thickness of the insulation layers required in the WUFI models are sometimes unrealistic from a market availability perspective (such as extremely thin layers, i.e. thinner than 20mm or extremely thick layer, i.e. thicker than 100mm – or even 50mm in the case of calcium silicate insulation boards).

This adjustment approach was used for the assessment, despite using unrealistic build-ups sometimes. It allows for equivalent comparison between the build-ups and the modelling still provides sufficient results for an accurate qualitative analysis of the impact of the insulation thickness on the hygrothermal performance of the build-up.

4.2. Additional Scenario Variations (Sensitivity Analysis)

Potential sensitivity analysis includes the following:

- <u>Change in internal moisture load = Cases X.a</u>
  Change in internal moisture load from ‘normal’ to ‘high’ following the guidance in BS EN 15026 (2007).

- <u>Change in external surface performance = Cases X.b</u>
  Introduction of additional moisture ingress through the external surface of the construction to simulate ‘imperfect’ construction, using the ASHRAE 160 method, with a rain penetration factor of 0.5%, 1% and 1.5% as a proxy for poor workmanship.
- <u>Change in orientation = Cases X.c</u>
  Change in orientation from ‘south-west’ (façade subject to the most

extreme conditions in wind-driven rain and solar gains) to 'north' (façade in much more reduced / protected conditions regarding both wind-driven rain and solar gains) to analyse the impacts both solar gains and wind-driven rain have on the presence of diffusion in winter and reverse diffusion in summer

- <u>Change in substrate and insulation materials = Cases X.d</u>
  Change in material in WUFI build-up

- <u>Other changes = Cases X.e</u>
  Other changes deemed necessary or useful after analysis of baseline and additional scenarios, will be modelled

Additional scenario variations will be determined on a case-by-case basis. More scenarios will be modelled on construction types that are considered with the highest risk of condensation, where possible.

5. WUFI Modelling - Construction Types

The retrofit report M7 highlighted that build-ups retrofitted with internal wall insulation (IWI) tended to be risky build-ups and displayed poor hygrothermal performance. Therefore, some construction typologies have been chosen to some additional WUFI analysis, as shown in the table below.

These build-ups are also retrofitted with three typical vapour-open insulation materials (rather than typical vapour-closed insulation materials as done in the M7 retrofit report).

Results and analysis are included below.

Table 5: Retrofit Typologies analysed

	Construction Type
R8	Solid masonry wall Retrofit Measure: Internal Wall Insulation (IWI) with: • Wood fibre insulation • Calcium silicate insulation boards • Sheep's wool insulation
R11.1	Cavity masonry (uninsulated) Retrofit Measure: Internal Wall Insulation (IWI) with: • Wood fibre insulation • Calcium silicate insulation boards • Sheep's wool insulation
R11.3	Partial-fill cavity masonry Retrofit Measure: Internal Wall Insulation (IWI) with: • Wood fibre insulation • Calcium silicate insulation boards • Sheep's wool insulation
R12	Full-fill cavity masonry Retrofit Measure: Internal Wall Insulation (IWI) with: • Wood fibre insulation • Calcium silicate insulation boards • Sheep's wool insulation

6. Typology R8: Solid masonry wall Retrofit Measure: Internal Wood Fibre Wall Insulation (IWI)

The R8 typology is an uninsulated solid brick wall prior to retrofit. The retrofit measure is to insulate the wall internally with Wood Fibre insulation.

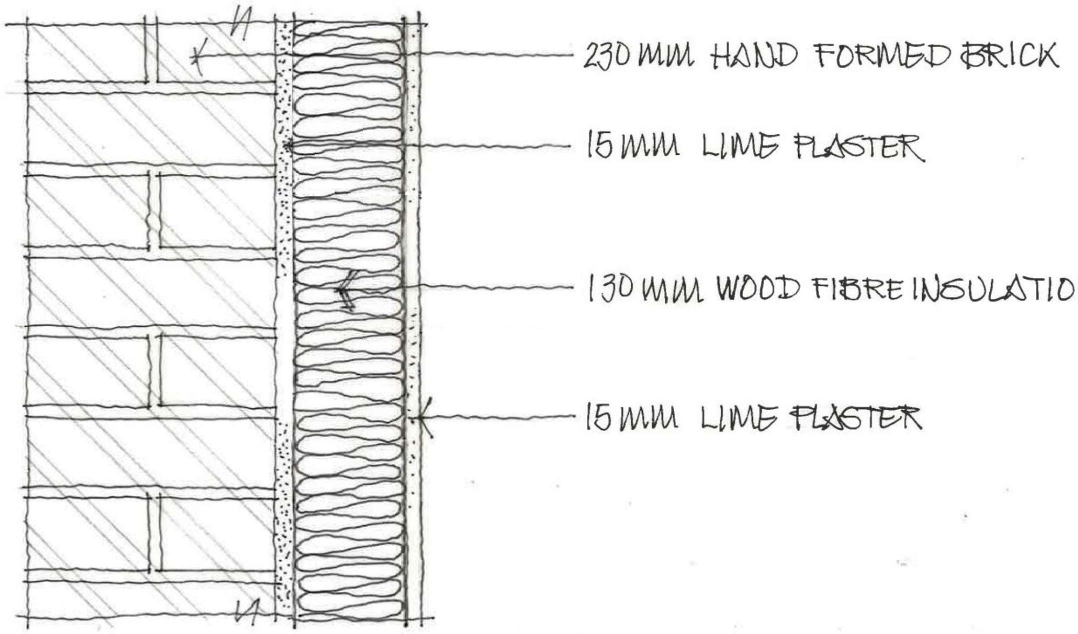


Figure 5: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

6.1. Assessment Method

As the solid brick layer is exposed, the capacity for moisture storage in this layer, as well as the exposure of its external surface to wind-driven rain, wind and solar gains throughout the year, play an impact on the hygrothermal performance of the build-up. As these elements need to be taken into account but fall outside of the scope of the BS EN ISO 13788 (2012) assessment method, this method cannot be used to provide an accurate assessment.

It is also worth noting that the STBA/DECC's ‘Moisture Risk Assessment and Guidance’ (2014) document states that ‘the advice given on Internal Wall Insulation onto solid masonry walls in section G.3.1.4 of BS 5250 (2011) is now considered incorrect (rather than just incomplete).’, and that BS5250 (2016) now advised that solid walls with internal insulation should be assessed using BS EN 15026.

6.2. Build-up

6.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 230mm solid brick (WUFI material: solid brick (hand-formed))
- 15mm lime plaster (assumed no wallpaper finish)

6.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are exposed to wind-driven rain and the brick material is a heavy weight material, with a high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

6.2.3. WUFI Build-up (post-retrofit)

Substrate:
Wood fibre insulation product installation generally requires a 'breathable' substrate on which to attach the insulation layer. Since the original build-up of this wall type already has a lime plaster finish – which is considerate to be an adequate substrate, this is retained along with an additional 5mm 'adhesive' layer with hygrothermal properties similar to that of lime plaster is used both to provide a smooth surface and to help support the wood fibre insulation installation.

In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Build-Up:

- 230mm solid brick (WUFI material: solid brick (hand-formed))
- 15mm lime plaster (assumed no wallpaper finish)
- 5mm lime plaster (as adhesive)
- 45/130/230 mm Wood fibre insulation (λ = 0.045 W/mK)
- 15mm lime plaster

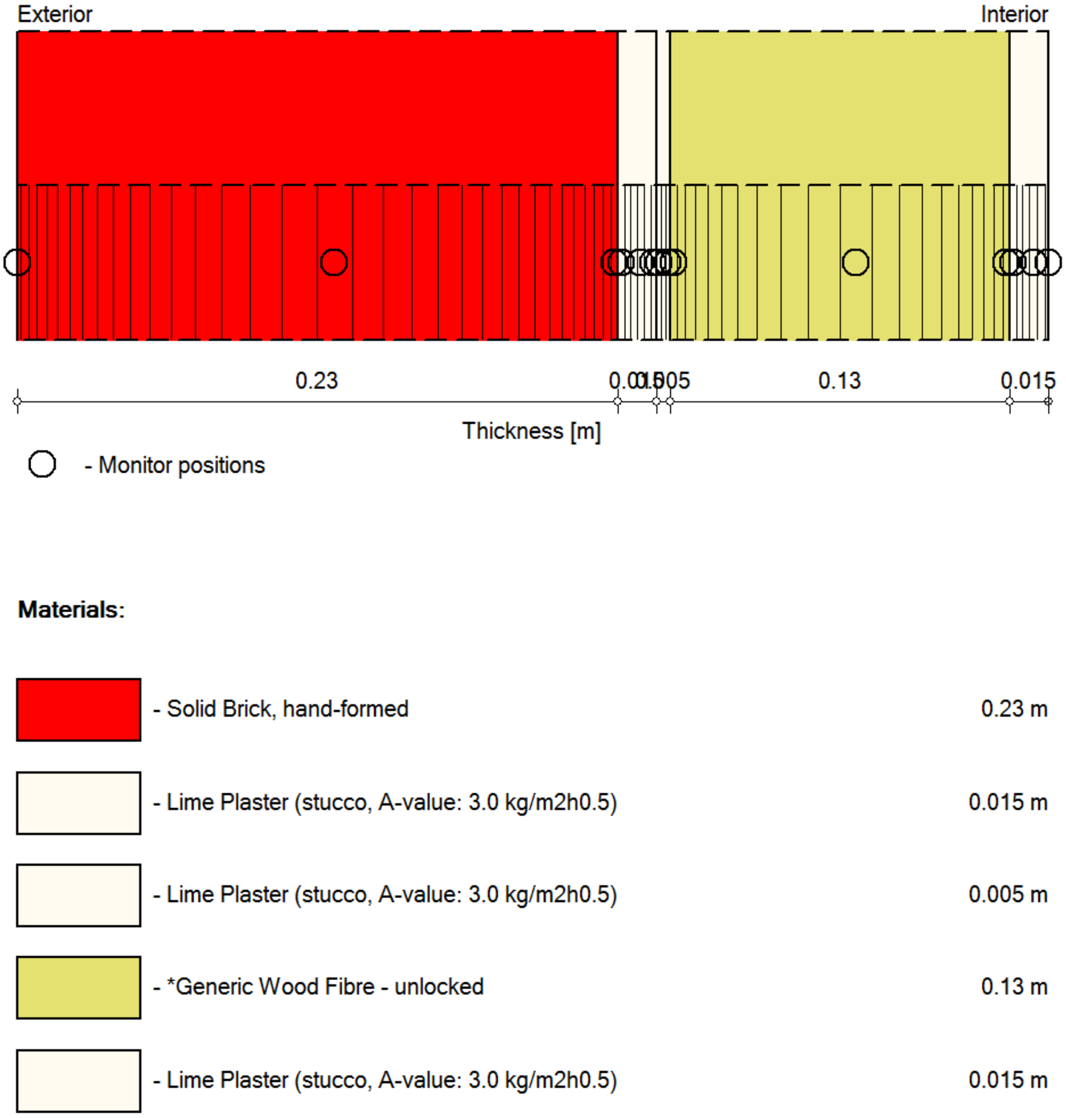


Figure 6 - Part L build-up used for WUFI model

Material Physical Properties

While the relevant material properties of the modern construction materials are reasonably consistent and well understood (e.g. gypsum board, rigid insulation, etc.), there is currently a lack of properly tested data for existing UK bricks, stones and plasters.

As this work is generic (no tested data is available), bricks already available in the existing WUFI Pro Fraunhofer database were assumed and selected as being the nearest matches to existing brick walls, based on the restricted level of information currently available. These selections were done to obtain a suitable range of data to model brick walls. In the absence of data, it is considered best to opt for conservative assumptions. In this situation, this means that the brick chosen to be used in this WUFI modelling is a less ‘performing’ brick in terms of moisture, i.e. a more ‘absorbent’ brick.

Default Brick

The “Solid Brick, hand-formed” from the Fraunhofer IBP database of materials was selected during the setting out of the methodology for this modelling work. This brick is a higher density, less porous brick with a high A-value (0.300 $kg/m^2\sqrt{s}$) – refer to Appendix A for full characteristics. The selection of this brick was based on a paper which tested the A-value of a typical London Brick Fletton brick at 0.32 $kg/m^2\sqrt{s}$ (Rirsch & Zhang, 2012). This is one of the few known moisture tests of a UK brick with publicly available results.

In the absence of what is considered a ‘typical’ brick in the industry, including full physical properties, the decision was taken to use this brick as the default brick in this modelling work. This is also one of the most absorbent bricks in the Fraunhofer WUFI database and therefore should give a good representation of “worst case scenario” in terms of brick characteristics.

6.3. Baseline Results

6.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the cases meeting the Part C, Part L and TER target U-values, as set out below.

Table 6: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

6.3.2. Critical Junction

For this typology, the focus is given on RH levels at the interface between the retrofitted insulation and the plastered solid wall.

This interface is correctly identified in BS 5250 (2011), which states: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*.

6.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the retrofitted insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

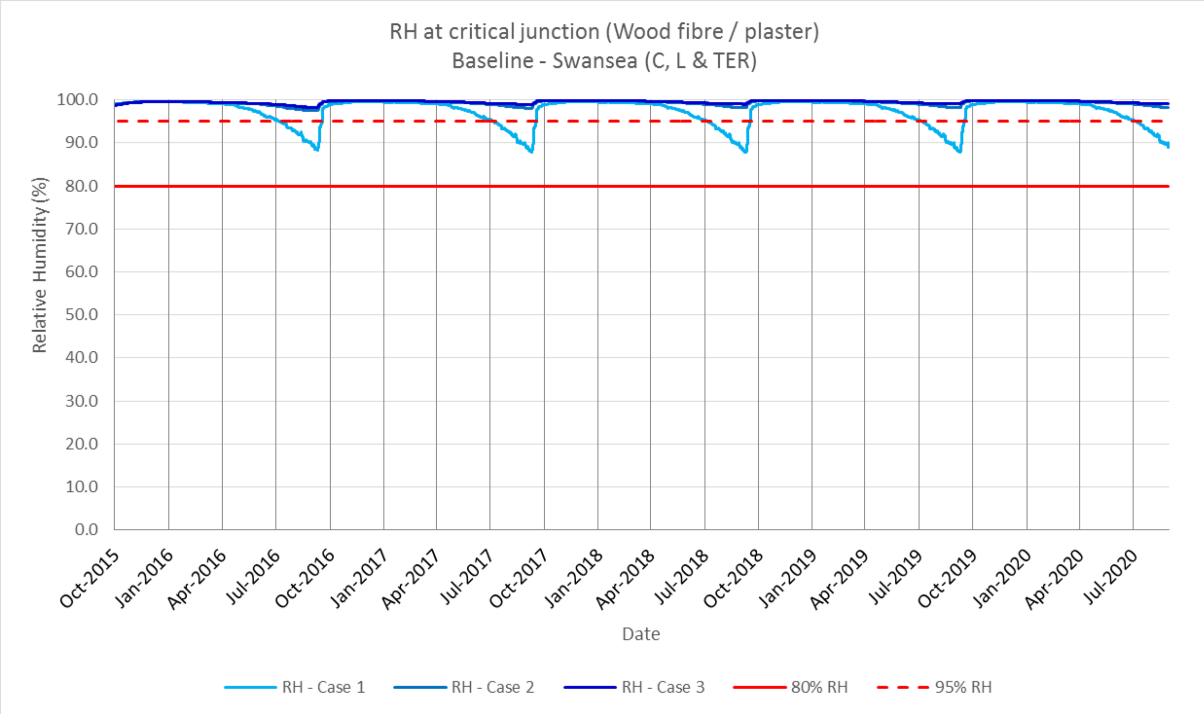


Figure 7: RH levels at critical junction for exposure zone 4

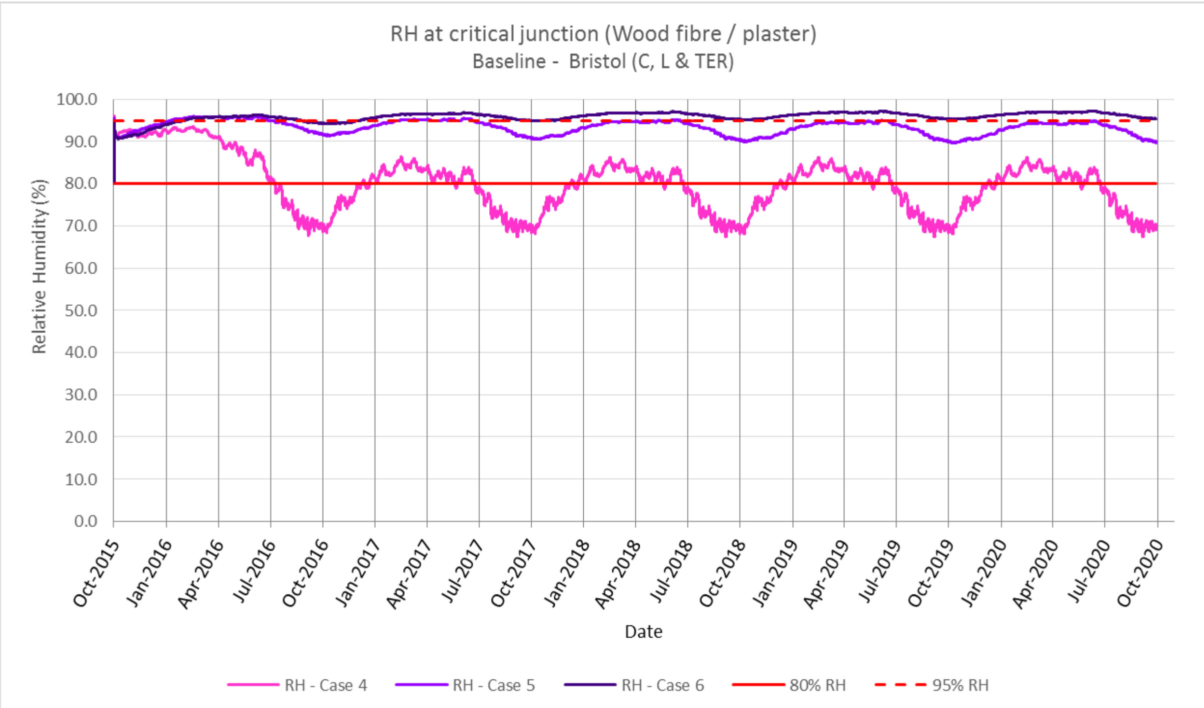


Figure 8: RH levels at critical junction for exposure zone 3

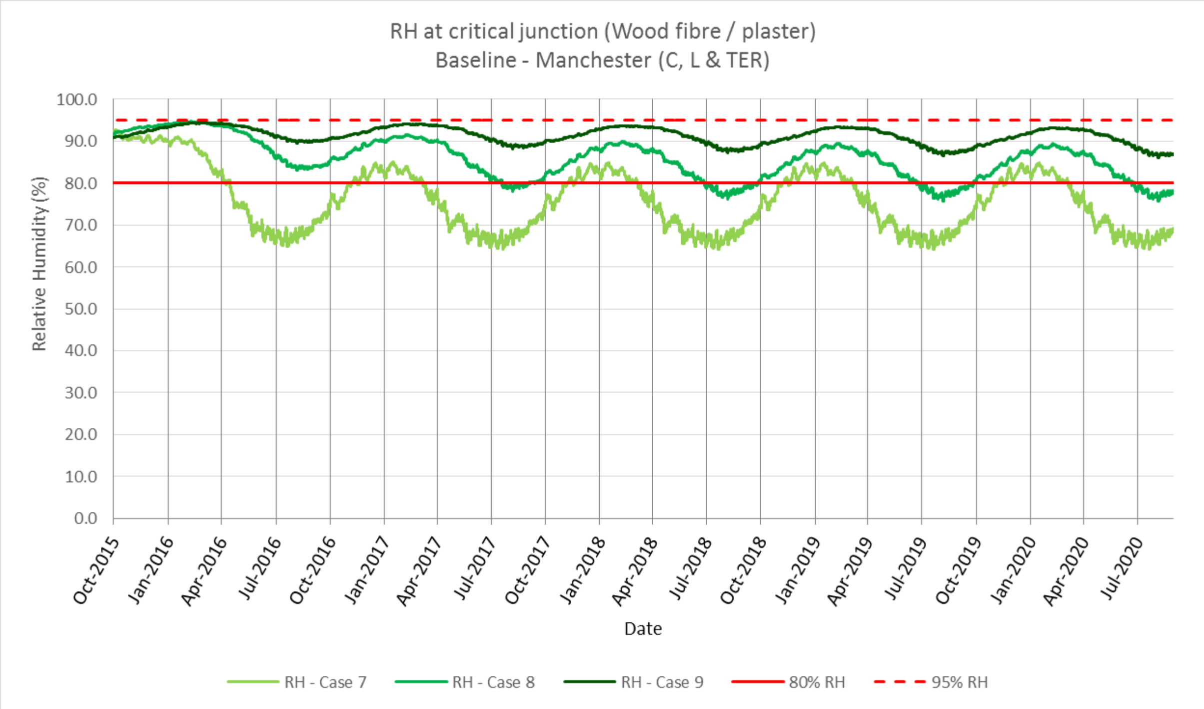


Figure 9: RH levels at critical junction for exposure zone 2

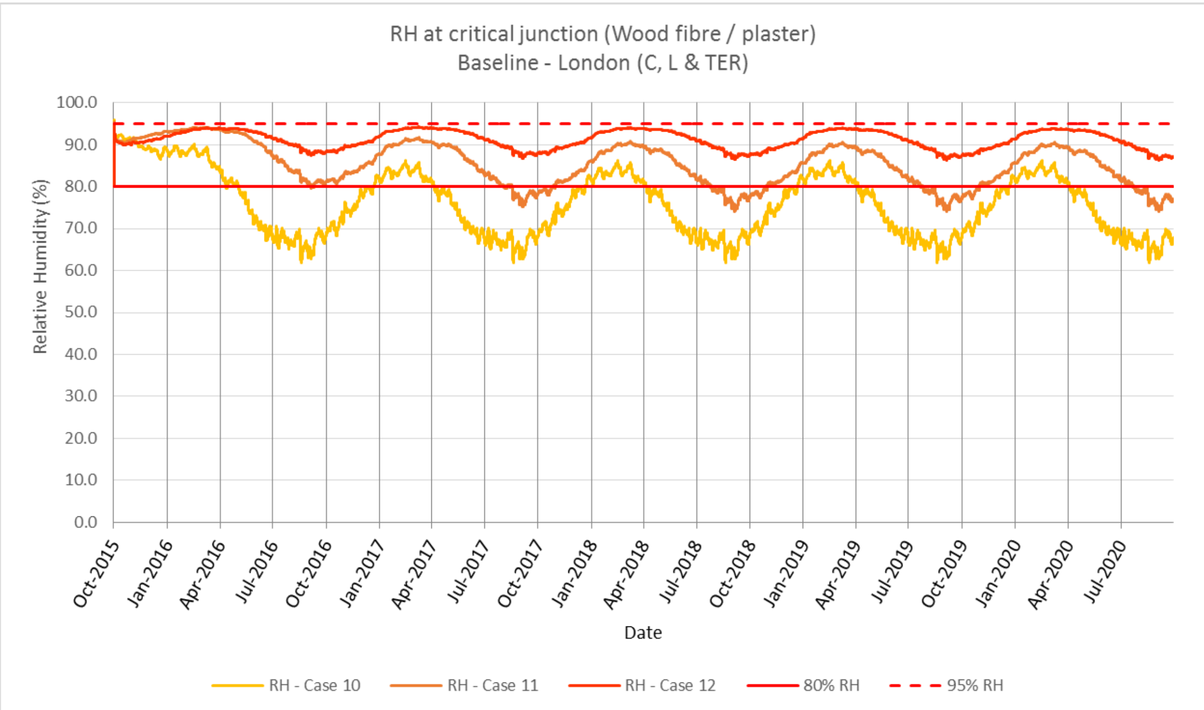


Figure 10: RH levels at critical junction for exposure zone 1

6.3.4. Results Analysis

Moisture risk assessment criteria

The 80% RH threshold cannot automatically be relaxed to 95% for this critical junction, as the build-up includes a material (brick) that allows driving rain ingress. (See section 2.3)

All scenarios achieve equilibrium. However, all scenarios display RH levels well above 80% for long periods of time for the Part C cases, and throughout the modelling period for Part L & TER cases. The cases in the highest exposure zone (Zone 4 – Swansea) reach saturation several months per year, meaning interstitial condensation is occurring at the critical junction.

These results are summarised in the table below.

Results

Table 7: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Fail	Fail	Fail	Fail
Part L	Fail	Fail	Fail	Fail
TER	Fail	Fail	Fail	Fail

Peak RH levels occur mainly in winter (as the driving factor is rainwater ingress, which tends to happen in Oct-Dec). So, despite high RH levels, the temperature is not sufficient to encourage interstitial mould growth. However, with increasing levels of insulation, the peak can be seen to shift towards spring – which then could push the critical junction into conditions where the temperature at the critical junction is warm enough to encourage mould growth.

These findings are in line with current concerns in the industry, as highlighted in Section 14.4 by the STBA/DECC's 'Moisture Risk Assessment and Guidance' (2014) and by the fact that this build-up is known as a risky build-up currently in the industry.

The main moisture source creating problems in a solid wall build-up is rain penetration from outside. As the wall, in this scenario, is not protected and the outer layer is very absorbent, moisture (as liquid water) penetrates deeper into the build-up in winter via capillary action due to wind-driven rain reaching the façade. Similarly, moisture (as water vapour) is also pushed back into the build-up in summer due to reverse diffusion (see definition in Glossary).

Effects of exposure zones

The effect of wind-driven rain exposure zones can be clearly seen on the graphs, with the case in Zone 4 – Swansea reaching interstitial condensation, while the other cases display very high RH levels (often > 95%) but without the presence of interstitial condensation. The exposure zones appear to only have a medium effect on the hygrothermal performance of the build-up, as this build-up is a very risky build-up to start with.

Effects of U-value

As expected with internal wall insulation; the higher the level of insulation, the higher the RH levels at the critical junction, due to the critical junction temperature being made colder. This shows that thermal efficiency and moisture risk management requirements conflict with each other.

In practice, the levels of insulation required in order to achieve the TER or even Part L U-value targets is unlikely to be installed since the insulation would be 'too thick' to be practically installed.

6.3.5. Conclusions – Baseline

As all the baseline scenarios fail quite significantly, independently of which wind-driven rain exposure zone the build-up is located in, this typology appears to be a very risky build-up and therefore cannot be recommended – as this exact build-up – as a safe method of construction in terms of resistance to moisture.

6.4. Conclusions

- BS EN 15026 is the only adequate method (though still not standardised)
- Build-up very risky in ‘theoretical’ conditions

7. Typology R8: Solid masonry wall Retrofit Measure: Internal Calcium Silicate Board Wall Insulation (IWI)

The R8 typology is an uninsulated solid brick wall prior to retrofit. The retrofit measure is to insulate the wall internally with Calcium Silicate Board insulation.

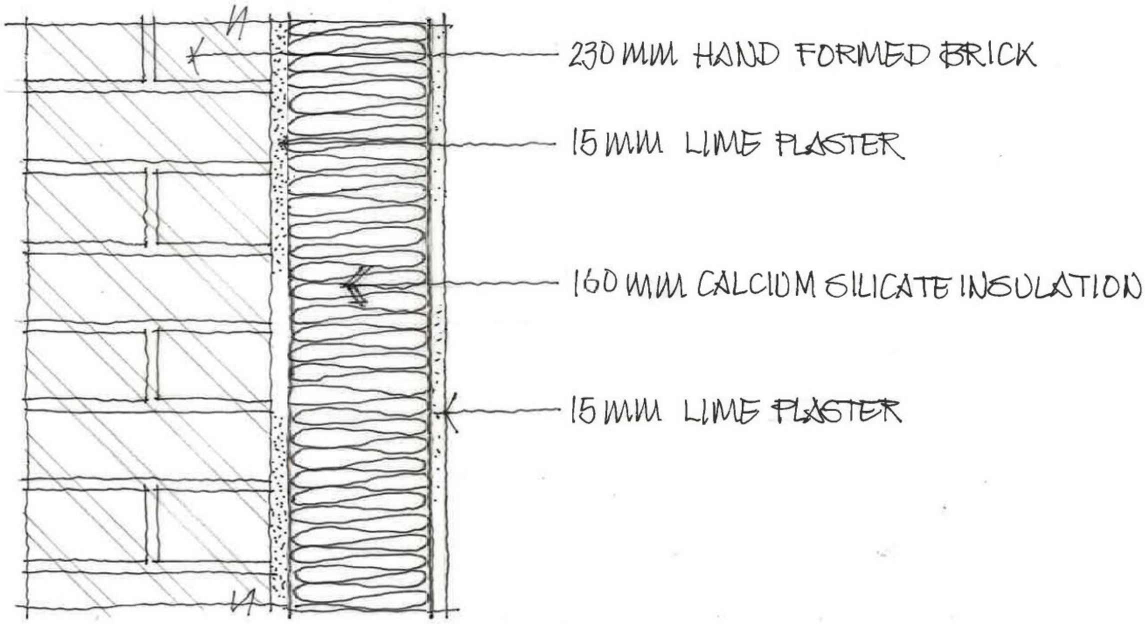


Figure 11: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

7.1. Assessment Method

As the solid brick layer is exposed, the capacity for moisture storage in this layer, as well as the exposure of its external surface to wind-driven rain, wind and solar gains throughout the year, play an impact on the hygrothermal performance of the build-up. As these elements need to be taken into account but fall outside of the scope of the BS EN ISO 13788 (2012) assessment method, this method cannot be used to provide an accurate assessment.

Due to these limitations, this typology will be assessed with the BS EN 15026 (2007) assessment method using WUFI modelling.

7.2. Build-up

7.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 230mm solid brick (WUFI material: solid brick (hand-formed))
- 15mm lime plaster (assumed no wallpaper finish)

7.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are exposed to wind-driven rain and the brick material is a heavy weight material, with a high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

7.2.3. WUFI Build-up (post-retrofit)

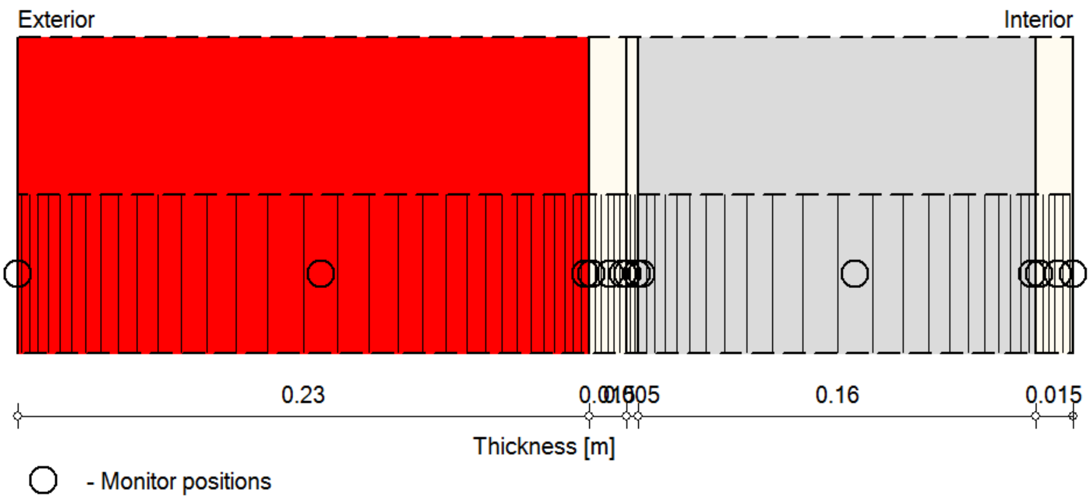
Substrate
Calcium Silicate board product installation generally requires a 'breathable' substrate on which to attach the insulation layer. Since the original build-up of this wall type already has a lime plaster finish – which is considered to be a adequate substrate, this is retained along with an additional 5mm adhesive layer (cementitious dry mortar).

The WUFI material “SAKRET Klebe- und Armierungsmörtel leicht KAM-L” is considered to closest WUFI material to represent the cementitious dry mortar adhesive material, to provide a smooth surface and to help fix the calcium silicate insulation boards.

Retrofitted Insulation Layer Thicknesses
In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Build-Up:

- 230mm solid brick (WUFI material: solid brick (hand-formed))
- 15mm lime plaster (assumed no wallpaper finish)
- 5mm Adhesive layer
- 55/160/280 mm Calcium Silicate board insulation (λ = 0.055 W/m.K)
- 15mm lime plaster



Materials:

- Solid Brick, hand-formed	0.23 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m
- SAKRET Klebe- und Armierungsmörtel leicht KAM-L	0.005 m
- *Calcium Silikates - unlocked	0.16 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m

Figure 12 - Part L build-up used for WUFI model

Material Physical Properties

While the relevant material properties of the modern construction materials are reasonably consistent and well understood (e.g. gypsum board, rigid insulation, etc.), there is currently a lack of properly tested data for existing UK bricks, stones and plasters.

As this work is generic (no tested data is available), bricks already available in the existing WUFI Pro Fraunhofer database were assumed and selected as being the nearest matches to existing brick walls, based on the restricted level of information currently available. These selections were done to obtain a suitable range of data to model brick walls. In the absence of data, it is considered best to opt for conservative assumptions. In this situation, this means that the brick chosen to be used in this WUFI modelling is a less 'performing' brick in terms of moisture, i.e. a more 'absorbent' brick.

Default Brick

The "Solid Brick, hand-formed" from the Fraunhofer IBP database of materials was selected during the setting out of the methodology for this modelling work. This brick is a higher density, less porous brick with a high A-value (0.300 $kg/m^2\sqrt{s}$) – refer to Appendix A for full characteristics. The selection of this brick was based on a paper which tested the A-value of a typical London Brick Fletton brick at 0.32 $kg/m^2\sqrt{s}$ (Rirsch & Zhang, 2012). This is one of the few known moisture tests of a UK brick with publicly available results.

In the absence of what is considered a 'typical' brick in the industry, including full physical properties, the decision was taken to use this brick as the default brick in this modelling work. This is also one of the most absorbent bricks in the Fraunhofer WUFI database and therefore gives a good representation of "worst case scenario" in terms of brick characteristics.

7.3. Baseline Results

7.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the cases meeting the Part C, Part L and TER target U-values, as set out below.

Table 8: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

7.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the retrofitted insulation and the existing plastered solid wall.

This interface is correctly identified in BS 5250 (2011), which states: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*.

7.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the retrofitted insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

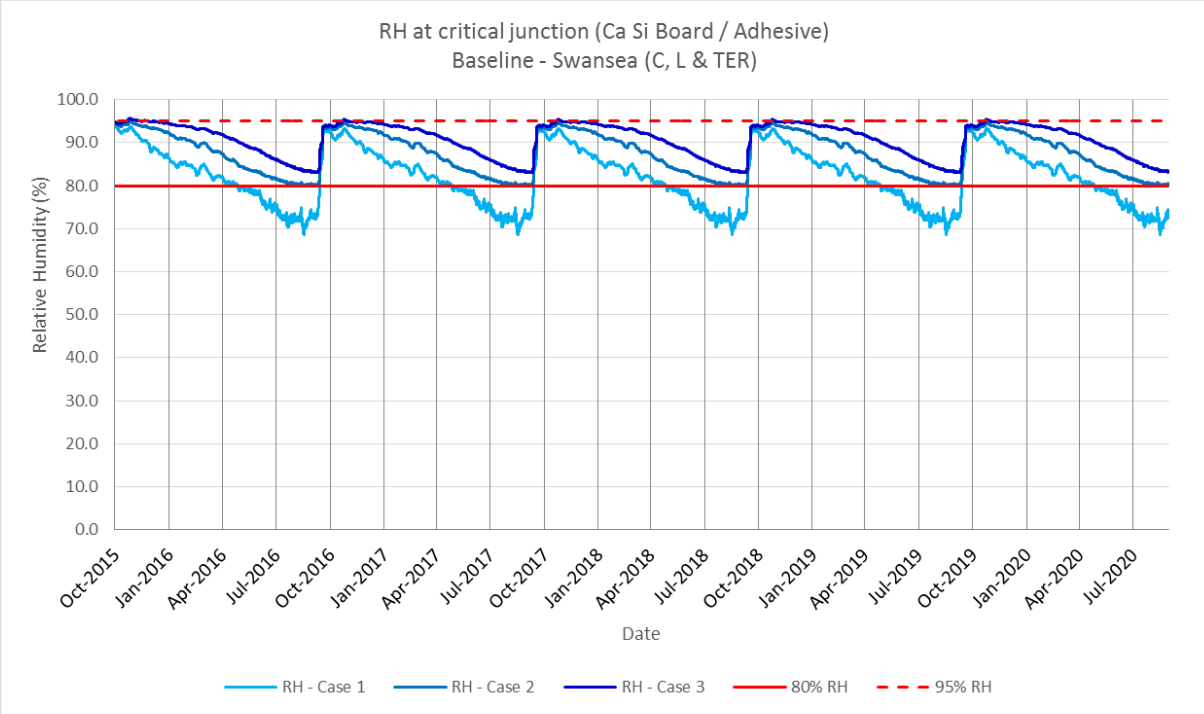


Figure 13: RH levels at critical junction for exposure zone 4

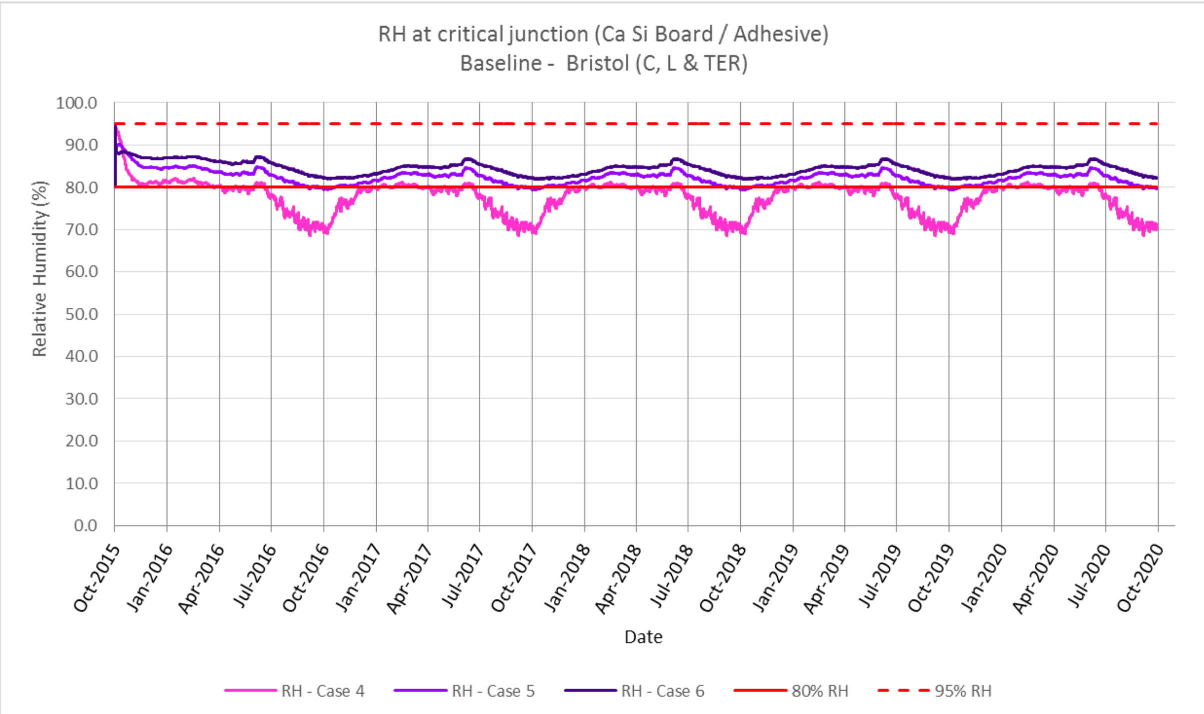


Figure 14: RH levels at critical junction for exposure zone 3

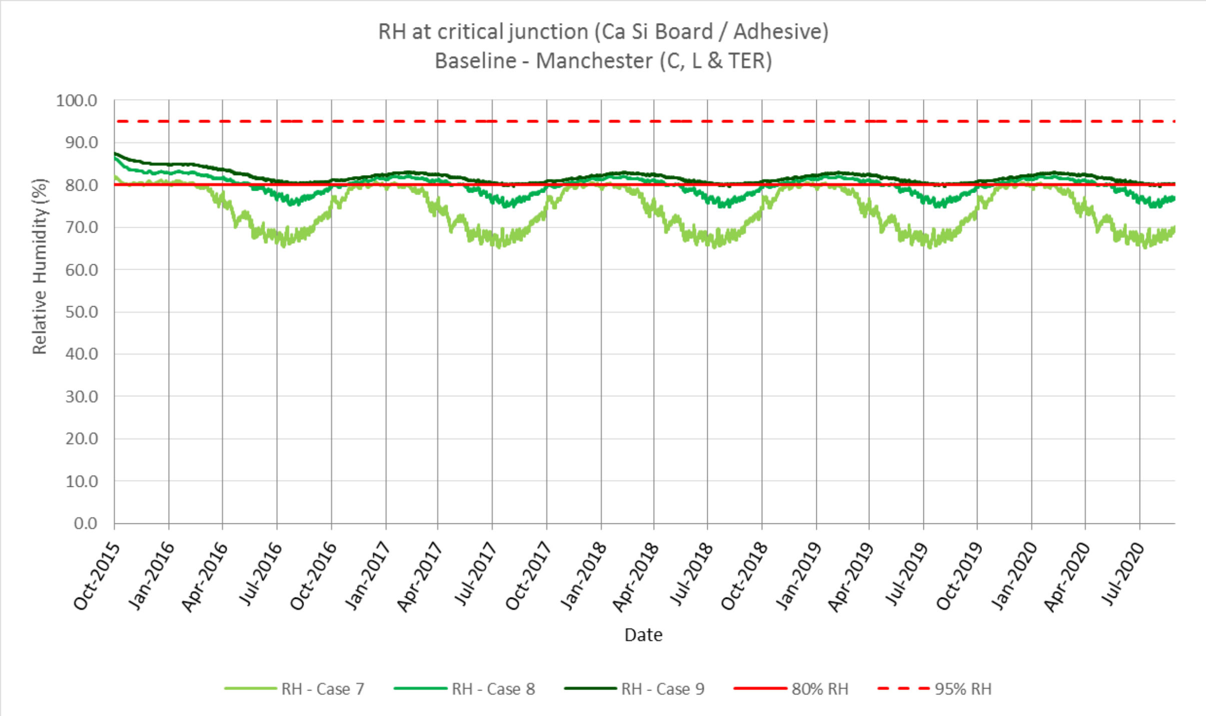


Figure 15: RH levels at critical junction for exposure zone 2

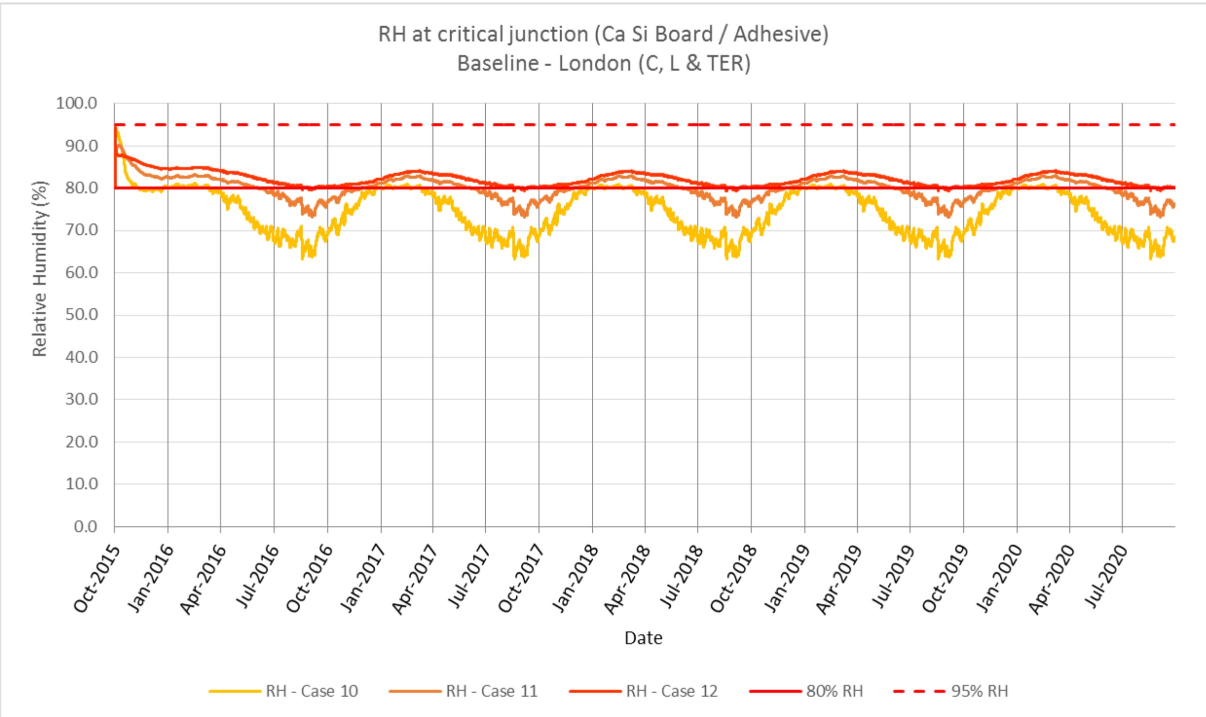


Figure 16: RH levels at critical junction for exposure zone 1

7.3.4. Results Analysis

Moisture risk assessment criteria

The 80% RH threshold cannot automatically be relaxed to 95% for this critical junction, as the build-up includes a material (brick) that allows driving rain ingress. (See section 2.3)

All scenarios achieve equilibrium. However, all Part L and TER scenarios display RH levels well above 80%, and Part C scenarios displaying levels at the 80% RH threshold (for cases outside exposure zone 4), which is still considered “risky”.

These results are summarised in the tables below.

Results

Table 9: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Fail	Risky	Risky	Risky
Part L	Fail	Fail	Fail	Fail
TER	Fail	Fail	Fail	Fail

Peak RH levels occur mainly in winter (as the driving factor is rainwater ingress, which tends to happen in Oct-Dec). So, despite high RH levels, the temperature is not sufficient to encourage interstitial mould growth. However, with increasing levels of insulation, the peak can be seen to shift towards spring – which then could push the critical junction into conditions where the temperature at the critical junction is warm enough to encourage mould growth.

These findings are in line with current concerns in the industry, as highlighted in Section 14.4 by the STBA/DECC's ‘Moisture Risk Assessment and Guidance’ (2014) and by the fact that this build-up is known as a risky build-up currently in the industry.

The main moisture source creating problems in a solid wall build-up is rain penetration from outside. As the wall, in this scenario, is not protected and the outer layer is very absorbent, moisture (as liquid water) penetrates deeper into the build-up in winter via capillary action due to wind-driven rain reaching the façade. Similarly, moisture (as water vapour) is also pushed back into the build-up in summer due to reverse diffusion (see definition in Glossary).

Effects of exposure zones

The effect of wind-driven rain exposure zones can be seen on the graphs, with the case in Zone 4 – Swansea reaching very high RH levels (> 95%) but without the presence of interstitial condensation. The exposure zones appear to only have a medium effect on the hygrothermal performance of the build-up, as this build-up is a very risky build-up to start with.

Effects of U-value

As expected with internal wall insulation; the higher the level of insulation, the higher the RH levels at the critical junction, due to the critical junction temperature being made colder. This shows that thermal efficiency and moisture risk management requirements conflict with each other.

In practice, the levels of insulation required in order to achieve the TER or even Part L U-value targets is unlikely to be installed since the insulation would be 'too thick' to be practically installed.

7.3.5. Conclusions – Baseline

As all the baseline scenarios fail quite significantly, independently of which wind-driven rain exposure zone the build-up is located in, this typology appears to be a very risky build-up and therefore cannot be recommended – as this exact build-up – as a safe method of construction in terms of resistance to moisture.

7.4. Conclusions

- BS EN 15026 is the only adequate method (though still not standardised)
- Build-up very risky in 'theoretical' conditions

8. Typology R8: Solid masonry wall Retrofit Measure: Internal Sheep's Wool Wall Insulation (IWI)

The R8 typology is an uninsulated solid brick wall prior to retrofit. The retrofit measure is to insulate the wall internally with Sheep's Wool insulation.

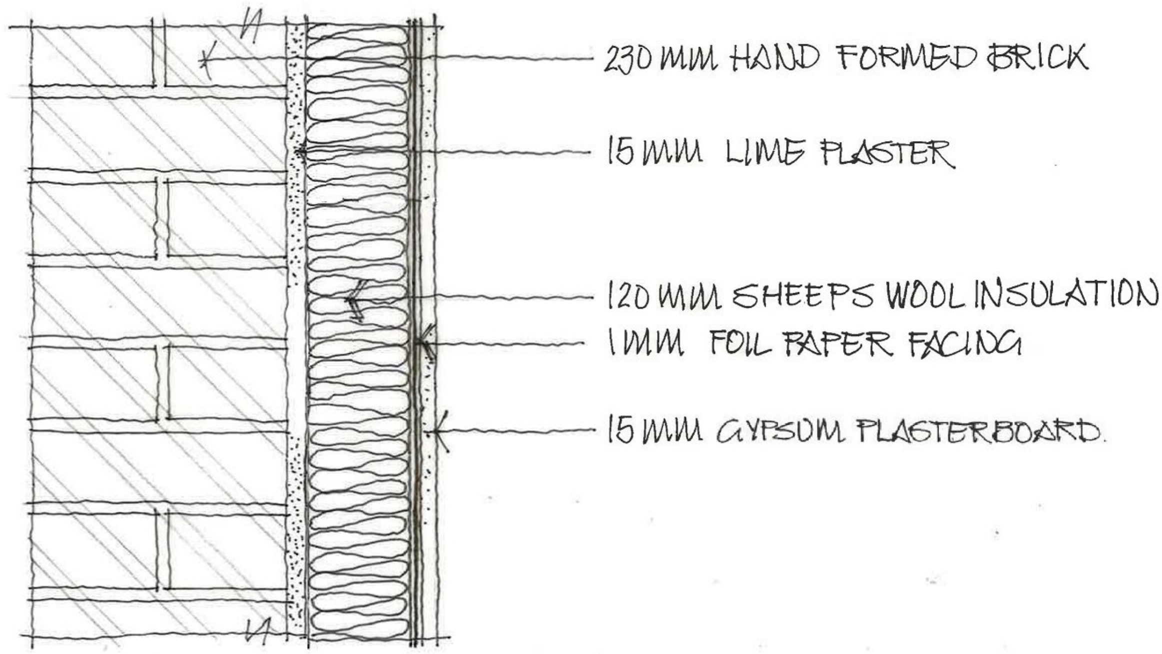


Figure 17: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

8.1. Assessment Method

As the solid brick layer is exposed, the capacity for moisture storage in this layer, as well as the exposure of its external surface to wind-driven rain, wind and solar gains throughout the year, play an impact on the hygrothermal performance of the build-up. As these elements need to be taken into account but fall outside of the scope of the BS EN ISO 13788 (2012) assessment method, this method cannot be used to provide an accurate assessment.

Due to these limitations, this typology will be assessed with the BS EN 15026 (2007) assessment method using WUFI modelling.

8.2. Build-up

8.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 230mm solid brick (WUFI material: solid brick (hand-formed))
- 15mm lime plaster (assumed no wallpaper finish)

8.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are exposed to wind-driven rain and the brick material is a heavy weight material, with a high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

8.2.3. WUFI Build-up (post-retrofit)

Substrate
Sheep's wool insulation product installation guidance generally does not requires any particular substrate on which to attach the insulation layer. The original lime plaster finish is therefore retained. Sheep's wool insulation is typically installed between battens and finished with a foil backed plasterboard.

Retrofitted Insulation Layer Thicknesses
In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Build-Up:

- 230mm solid brick (WUFI material: solid brick (hand-formed))
- 15mm lime plaster (assumed no wallpaper finish)
- 40/120/215 mm Sheep's wool insulation (λ = 0.036 W/m.K) installed between timber battens
- 1mm foil paper facing (sd = 14m)
- 15mm gypsum plasterboard (including skim)

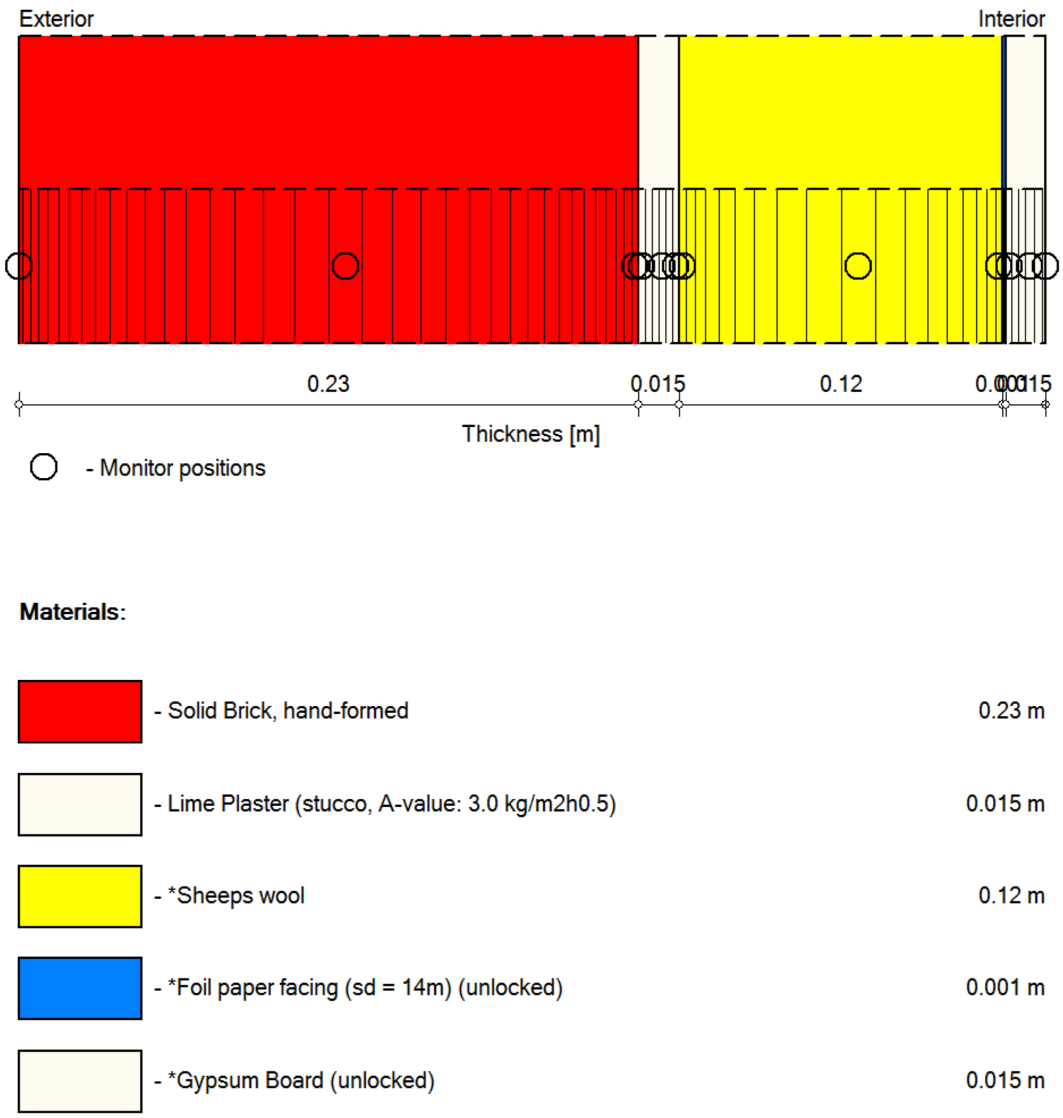


Figure 18 - Part L build-up used for WUFI model

Material Physical Properties

While the relevant material properties of the modern construction materials are reasonably consistent and well understood (e.g. gypsum board, rigid insulation, etc.), there is currently a lack of properly tested data for existing UK bricks, stones and plasters.

As this work is generic (no tested data is available), bricks already available in the existing WUFI Pro Fraunhofer database were assumed and selected as being the nearest matches to existing brick walls, based on the restricted level of information currently available. These selections were done to obtain a suitable range of data to model brick walls. In the absence of data, it is considered best to opt for conservative assumptions. In this situation, this means that the brick chosen to be used in this WUFI modelling is a less ‘performing’ brick in terms of moisture, i.e. a more ‘absorbent’ brick.

Default Brick

The “Solid Brick, hand-formed” from the Fraunhofer IBP database of materials was selected during the setting out of the methodology for this modelling work. This brick is a higher density, less porous brick with a high A-value (0.300 $kg/m^2\sqrt{s}$) – refer to Appendix A for full characteristics. The selection of this brick was based on a paper which tested the A-value of a typical London Brick Fletton brick at 0.32 $kg/m^2\sqrt{s}$ (Rirsch & Zhang, 2012). This is one of the few known moisture tests of a UK brick with publicly available results.

In the absence of what is considered a ‘typical’ brick in the industry, including full physical properties, the decision was taken to use this brick as the default brick in this modelling work. This is also one of the most absorbent bricks in the Fraunhofer WUFI database and therefore gives a good representation of “worst case scenario” in terms of brick characteristics.

8.3. Baseline Results

8.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the cases meeting the Part C, Part L and TER target U-values, as set out below.

Table 10: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

8.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the retrofitted insulation and the existing plastered solid wall.

This interface is correctly identified in BS 5250 (2011), which states: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*.

8.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the retrofitted insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

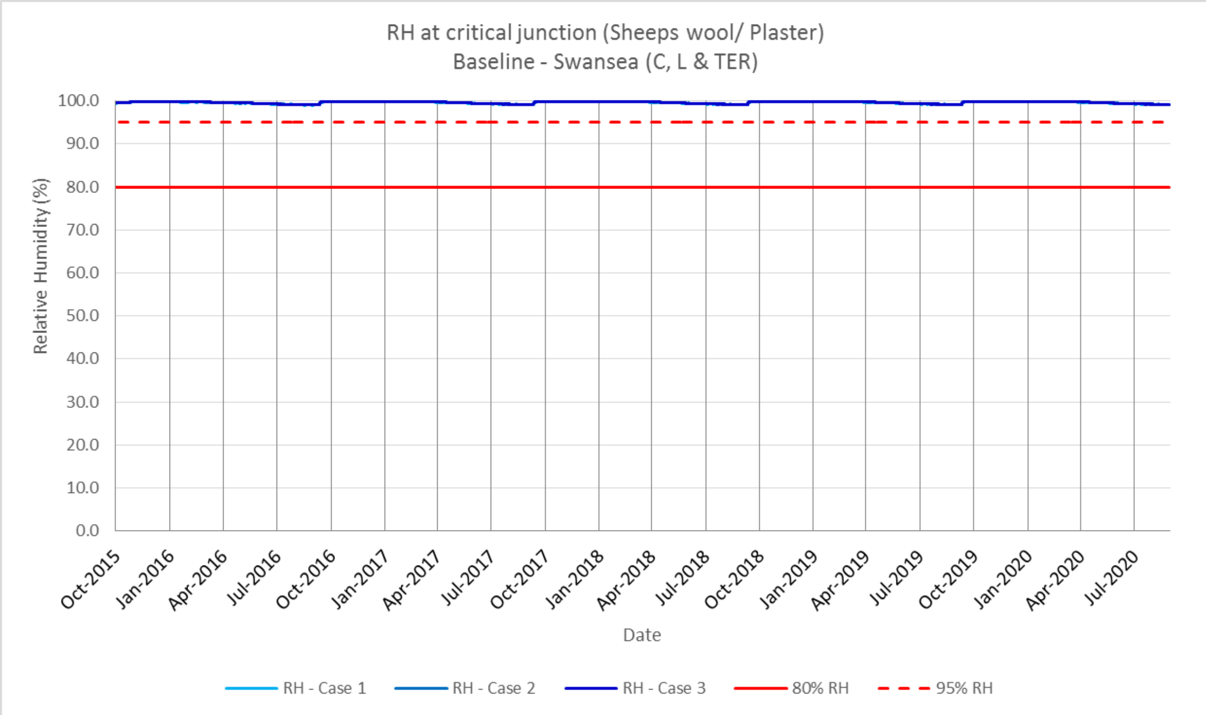


Figure 19: RH levels at critical junction for exposure zone 4

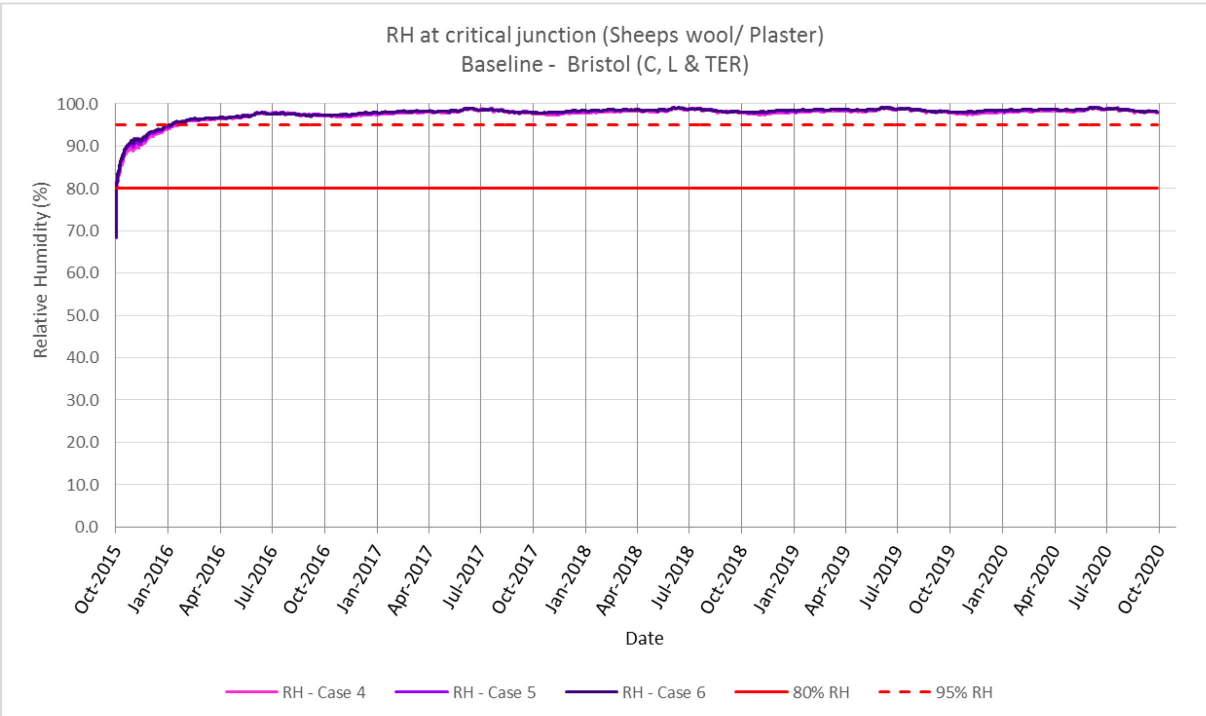


Figure 20: RH levels at critical junction for exposure zone 3

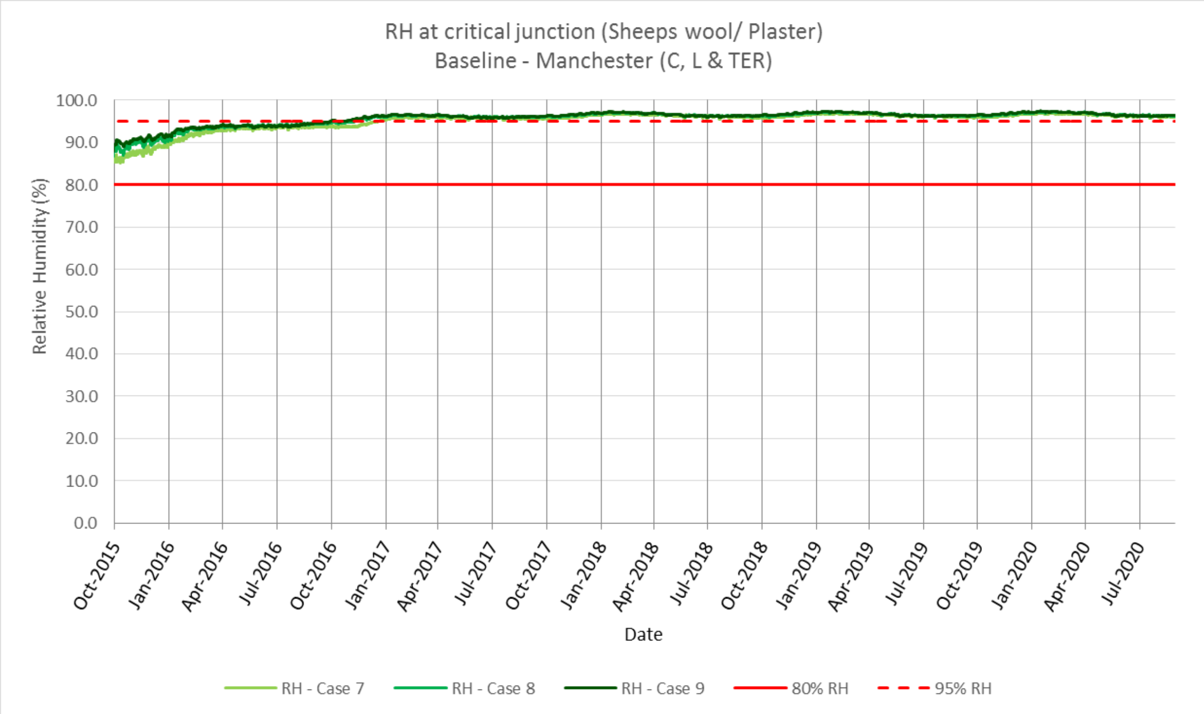


Figure 21: RH levels at critical junction for exposure zone 2

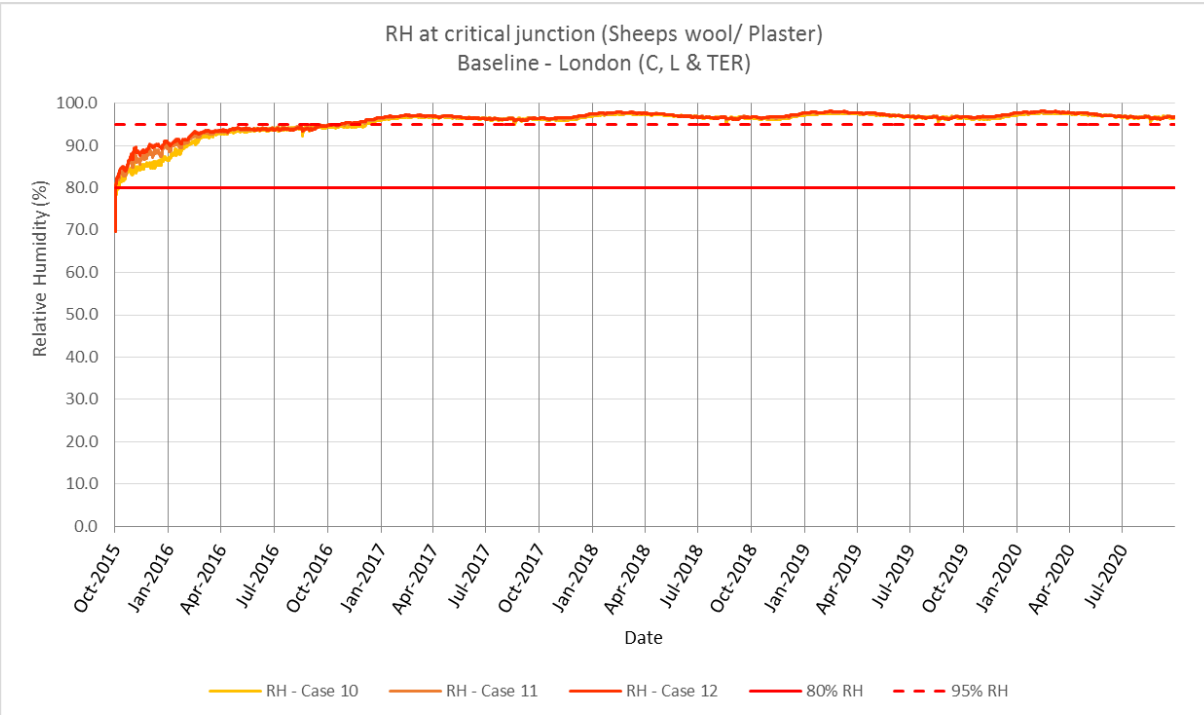


Figure 22: RH levels at critical junction for exposure zone 1

8.3.4. Results Analysis

Moisture risk assessment criteria

The 80% RH threshold cannot automatically be relaxed to 95% for this critical junction, as the build-up includes a material (brick) that allows driving rain ingress. (See section 2.3)

In addition, temperatures in summer at the junction are warm enough to support mould growth This means that suitable conditions are met at this critical junction for mould growth to potentially occur.

All scenarios achieve equilibrium. However, all scenarios display RH levels well above 80%, as well as above the 95% RH threshold. The case in the highest exposure zone (Zone 4 – Swansea) reaches saturation several months per year, meaning interstitial condensation is occurring at the critical junction.

These results are summarised in the tables below.

Results

Table 11: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Fail	Fail	Fail	Fail
Part L	Fail	Fail	Fail	Fail
TER	Fail	Fail	Fail	Fail

These findings are in line with current concerns in the industry, as highlighted in Section 14.4 by the STBA/DECC's 'Moisture Risk Assessment and Guidance' (2014) and by the fact that this build-up is known as a risky build-up currently in the industry.

The main moisture source creating problems in a solid wall build-up is rain penetration from outside. As the wall, in this scenario, is not protected and the outer layer is very absorbent, moisture (as liquid water) penetrates deeper into the build-up in winter via capillary action due to wind-driven rain reaching the façade. Similarly, moisture (as water vapour) is also pushed back into the build-up in summer due to reverse diffusion (see definition in Glossary). However, with insulation layer covered by a foil layer (acting like a VCL – if continuous) present internally to the solid wall, the moisture has nowhere to go and creates unfavourable conditions – leading to build-up failure – at the critical junction.

Effects of exposure zones

The effect of wind-driven rain exposure zones can be seen on the graphs, with the case in Zone 4 – Swansea reaching interstitial condensation, while the other cases display very high RH levels (> 95%) but without the presence of interstitial condensation. The exposure zones appear to only have a medium effect on the hygrothermal performance of the build-up, as this build-up is a very risky build-up to start with.

Effects of U-value

The RH levels between different insulation levels / target U-values is almost indistinguishable on the graphs. This shows that other factors like the wind-driven rain exposure zones, play a more significant role on the hygrothermal performance of the build-up.

8.3.5. Conclusions – Baseline

As all the baseline scenarios fail quite significantly, independently of which wind-driven rain exposure zone the build-up is located in, this typology appears to be a very risky build-up and therefore cannot be recommended – as this exact build-up – as a safe method of construction in terms of resistance to moisture.

8.4. Conclusions

- BS EN 15026 is the only adequate method (though still not standardised)
- Build-up very risky in ‘theoretical’ conditions

8.5. Sensitivity Analysis – Change in Build-up [Cases X.d]: Removal of AVCL

8.5.1. Sensitivity to presence of AVCL

This typology includes an AVCL between the inner plasterboard lining and the insulation, following BS 5250 (2011) advice. The sensitivity test is to remove this layer in order to test whether the 'breathability' of the insulation is compromised by the AVCL.

8.5.2. Sensitivity Analysis

The sensitivity analysis case is set in the wind-driven rain exposure zones with the best performance from the baseline assessment (London), and meeting the Part C target U-value (as per baseline case).

8.5.3. Graph at Critical Junction

The graph displayed below show the RH levels at the critical junction (which is the same as in the baseline cases), on the cold side of the retrofitted insulation layer.

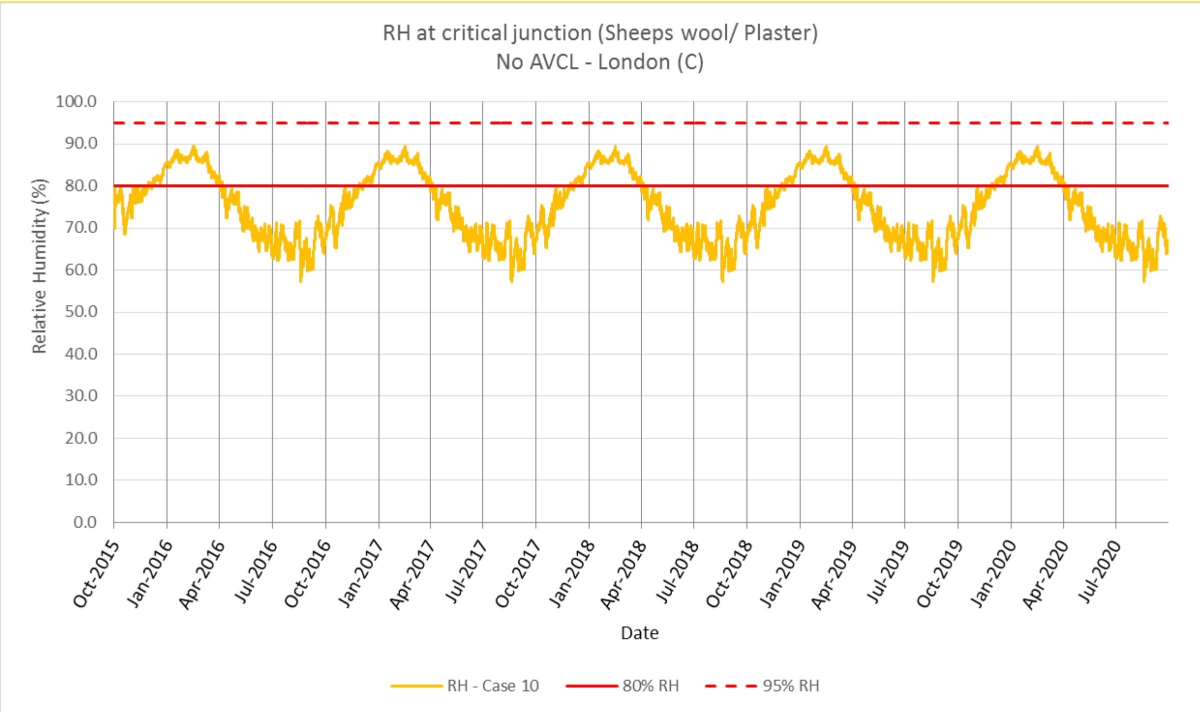


Figure 23: RH levels at critical junction for exposure zone 1

8.5.4. Timber Moisture Levels

As one of the materials at the critical junction is timber, considered a 'fragile' material, the water content in this layer is analysed.

Water content in material is normally expressed in kg/m3 (kg of water per m3 of materials). However, it is more helpful to express the water content of timber in mass – percent (M-%), as it is then easier to understand when timber is at risk of rotting. In these circumstances, the moisture content is expressed in percent as a ratio of the mass of water present in the timber by the mass of the oven dry timber (with the mass of the water being the difference between the weight of the wet timber and the oven dry timber).

Rot is caused by damp wood being attacked by fungi. In general, rot starts to develop when moisture levels in timber reach 20% or above. However, it is worth noting that moisture content in timber of around 18% already reduces the load-bearing capacity of structural wood elements.

Although the moisture content of the timber battens is not specifically modelled, the moisture content of the adjacent sheep's wool fluctuates annually between 8% and 11.5%.

8.5.5. Conclusions – Sensitivity Analysis Cases X.d

<u>Moisture risk assessment criteria</u>

The graph show that the case modelled in this sensitivity analysis performs better than the baseline cases, as the RH profile at the critical junction in the sensitivity analysis is kept consistently lower compared to its respective baseline.

However, this improvement in the hygrothermal performance of the build-up is not significant enough to change the status of the modelled case, as RH levels at the critical junction still stay above the 80% RH threshold for much of the year. This means that all sensitivity analysis cases retain the same status as the baseline cases, being considered a 'fail' in accordance with the moisture risk assessment criteria listed in section 2.3.

9. Typology R11.1: Cavity masonry (uninsulated) Retrofit Measure: Internal Wood Fibre Wall Insulation (IWI)

The R11.1 typology is an uninsulated cavity wall prior to retrofit. The retrofit measure is to insulate the wall internally with wood fibre insulation.

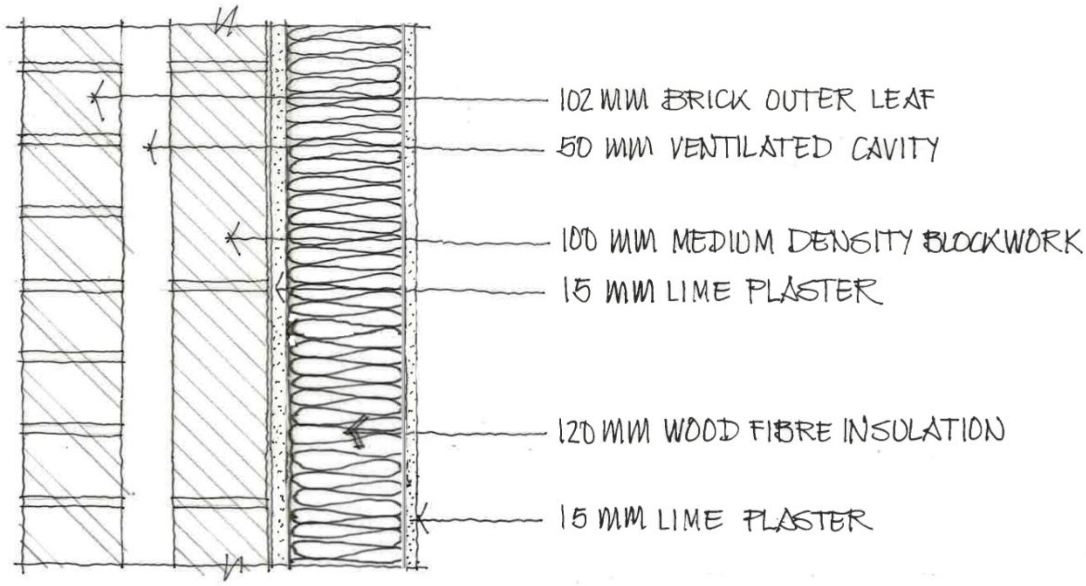


Figure 24: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

9.1. Assessment Method

As BS 5250 (2011) states in the cavity wall section (G.4.2.1), *'masonry walls of stonework, brickwork, blockwork or concrete may incorporate a cavity, the primary function of which is to prevent the transmission of rainwater to the interior. Rainwater might well penetrate the external skin of masonry, reducing its thermal resistance, and provision should be made for such moisture to drain out of the cavity.'*

To follow prescriptive guidance, the cavity is ventilated to the outside, to allow any moisture present in the cavity to be drained out. This means that the outer brick layer is considered as a 'protective cladding' and is not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the outer surface of the blockwork inner leaf to the internal finish.

As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations).

9.2. Build-up

9.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

9.2.2. Initial Conditions

Although the materials present in the pre-retrofit build-up are not exposed to wind-driven rain, the medium density blockwork is a heavy weight material, with high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

9.2.3. WUFI Build-up (post-retrofit)

Substrate:
Wood fibre product installation generally requires a 'breathable' substrate on which to attach the insulation layer. Since the original build-up of this wall type has a gypsum plaster finish – which is not considered to be an adequate substrate for the wood fibre insulation layer, this is replaced with a new lime plaster along with an additional 5mm 'adhesive' layer with hygrothermal properties similar to that of lime plaster (used to provide a smooth surface and to help support the wood fibre insulation installation).

In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 100mm medium density blockwork inner leaf
- 15mm lime plaster (replacing original gypsum plaster)
- 5mm lime plaster (as adhesive)
- 35/120/220 mm Wood fibre insulation (λ = 0.045 W/mK)
- 15mm lime plaster

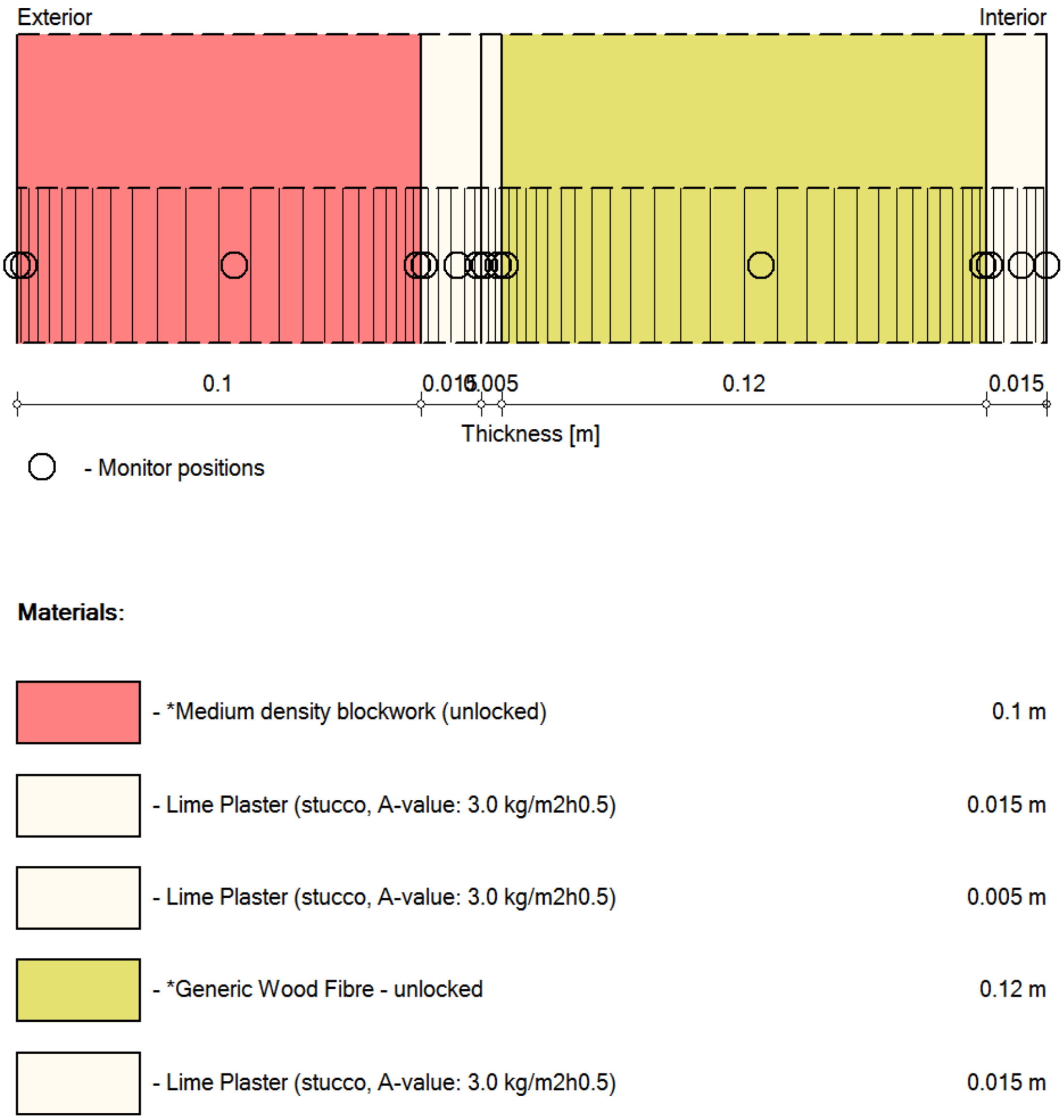


Figure 25 - Part L build-up used for WUFI model

WUFI Input Parameters

As the cavity is considered ventilated, both the brick outer layer and the ventilated air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the cold side of the inner leaf of blockwork) is exposed to different external conditions from exposed build-ups, due to the outer brick layer acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the outer brick layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the ‘sheltered’ condition in the cavity

9.3. Baseline Results

9.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the cases meeting the Part C, Part L and TER target U-values, as set out below.

Table 12: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

9.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the retrofitted insulation and the plastered inner blockwork wall leaf. This is in line with BS 5250 (2011) paragraph G.4.2.4 which states that: *‘Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation’*.

9.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the retrofitted insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

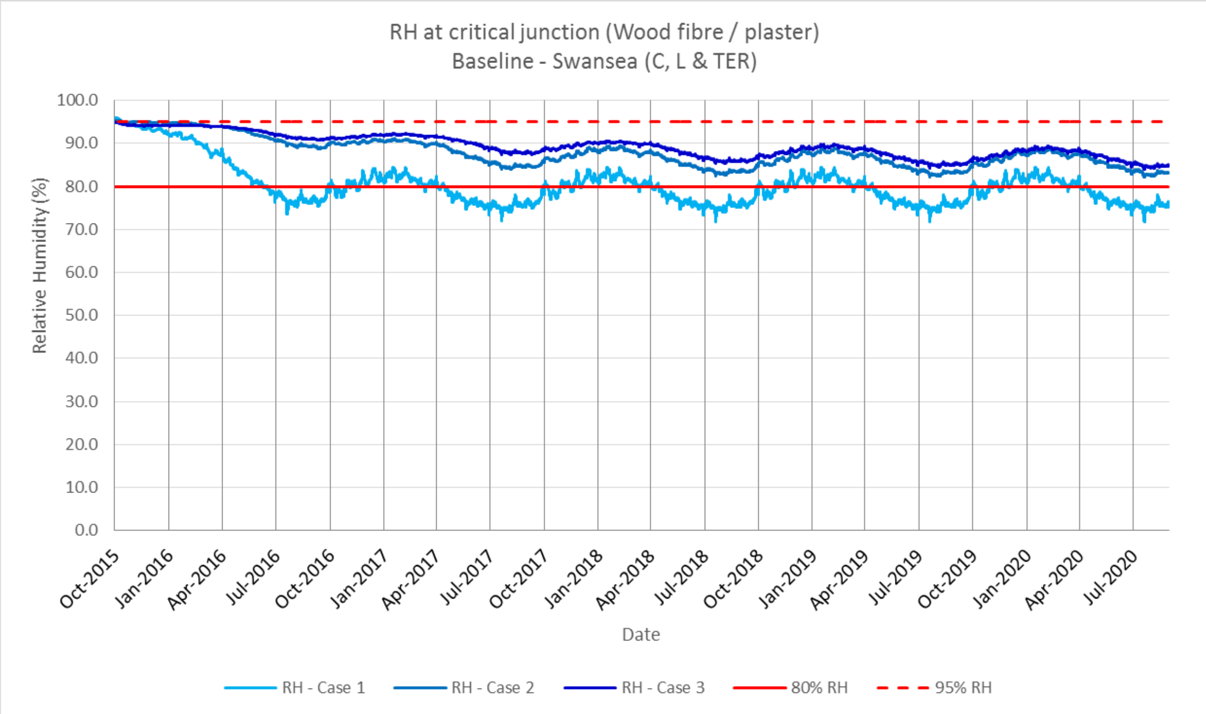


Figure 26: RH levels at critical junction for exposure zone 4

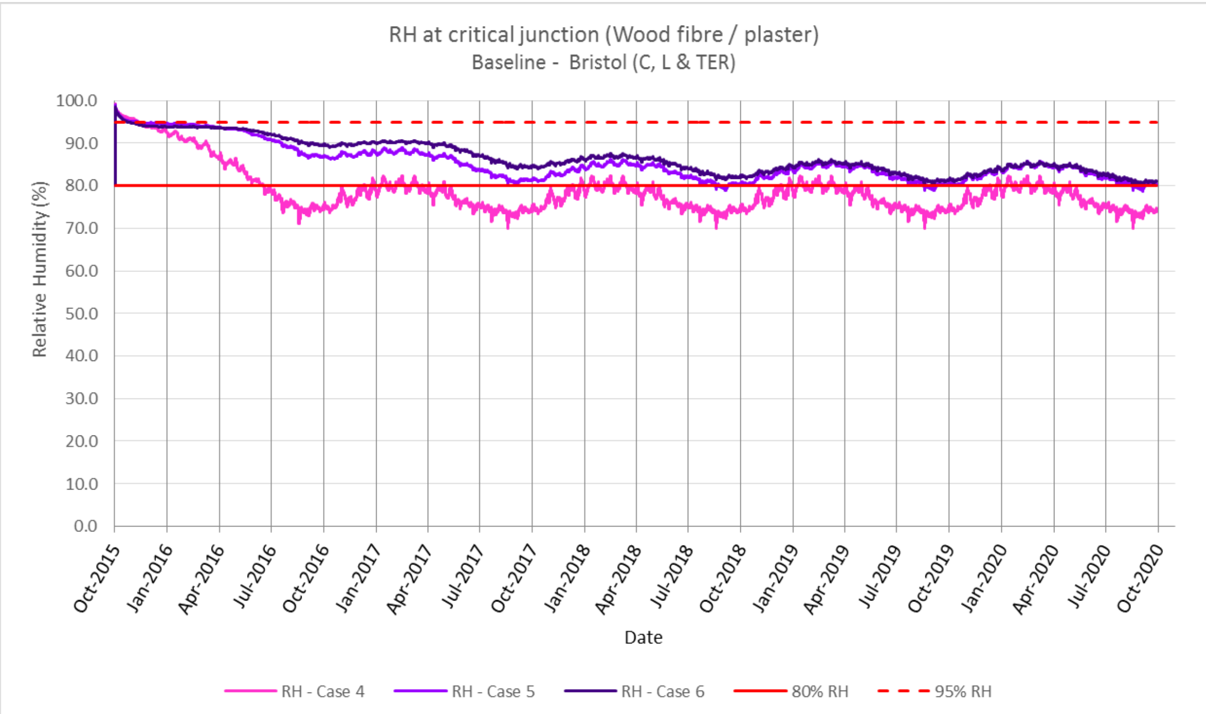


Figure 27: RH levels at critical junction for exposure zone 3

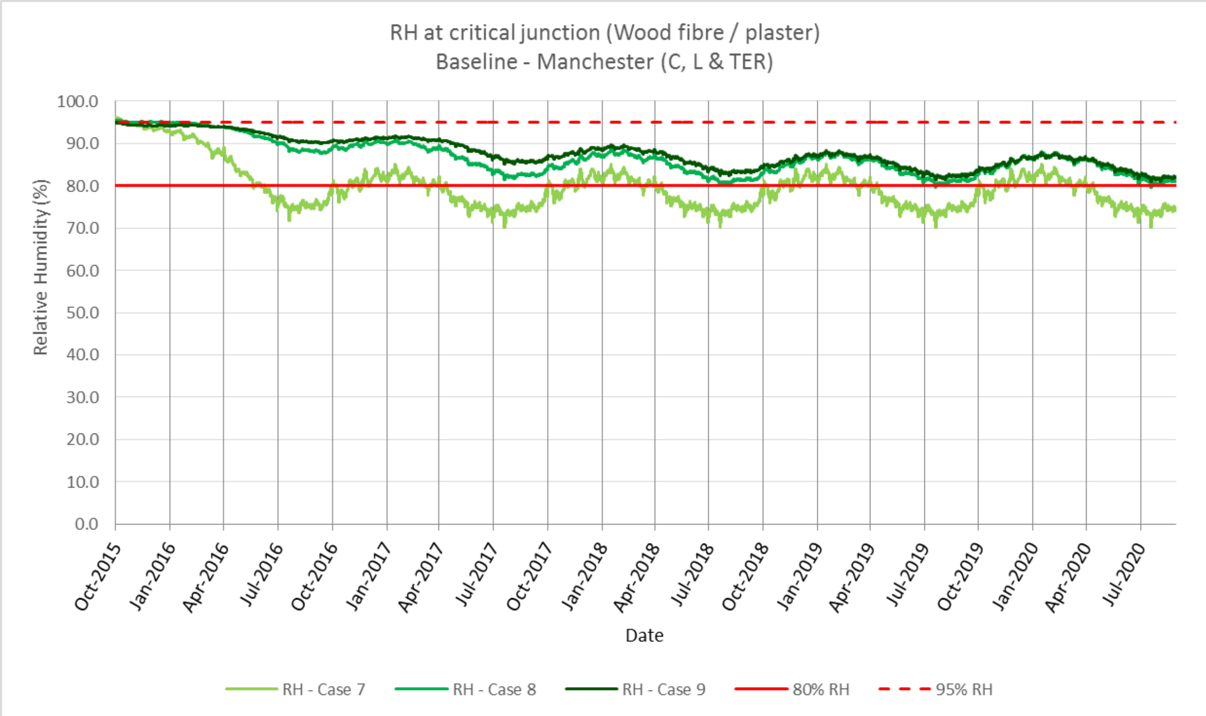


Figure 28: RH levels at critical junction for exposure zone 2

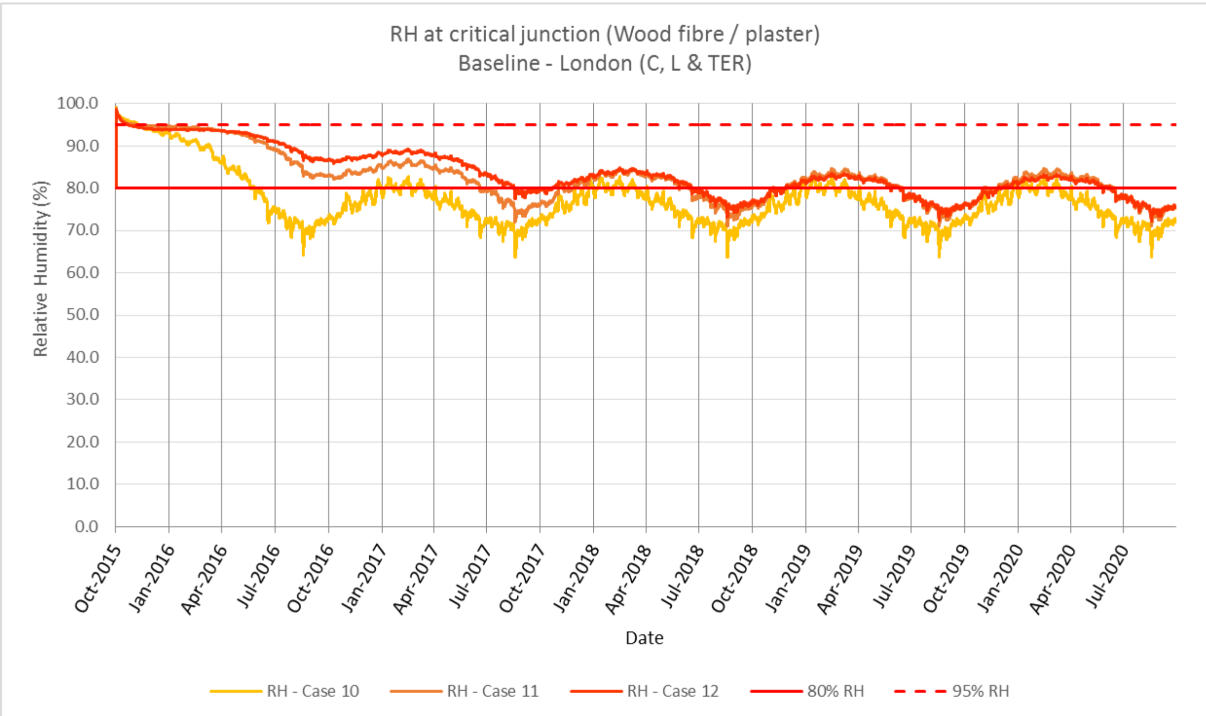


Figure 29: RH levels at critical junction for exposure zone 1

9.3.4. Results Analysis

Moisture risk assessment criteria

All scenarios achieve equilibrium. Part C, Part L and TER cases display RH levels significantly above the 80% threshold for large periods of time (in some cases continuously through the modelling period). The Part C cases for zone 3 and zone 1 are the only cases for which the 80% RH threshold is met for short amounts of time (less than a month at a time), but the average RH levels are still considered too high to declare these cases a “pass”.

In addition, all scenarios spend lengthy periods of time initially above the 80% RH threshold at the beginning of the modelling period. This is likely to be due to the high initial moisture levels in the lime plaster and adhesive layers.

However, the 80% RH threshold can be relaxed to 95% for this critical junction, as the build-up meets the four required criteria set out by WTA, 2009 (see section 2.3). For this reason, results showing the results based on the 95% RH threshold are also shown below.

Results

Table 13: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Fail	Risky	Fail	Risky
Part L	Fail	Fail	Fail	Fail
TER	Fail	Fail	Fail	Fail

Table 14: Summary of results with 95% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

The results show that the build-up can be considered safe in these precise conditions, thanks to the build-up meeting the WTA (2009) criteria to relaxed the RH threshold from 80 to 95%. Indeed, the conditions in which the build-up is installed (no air gap present at the critical junction, no ingress of wind-driven rain, use of vapour-open materials and normal internal moisture loads) mean that the risk of interstitial condensation is considered significantly reduced, despite average RH levels which can still be considered high.

Effects of exposure zones

The difference in exposure zones is noticeable on the graphs, with build-ups in zones that are more exposed to wind-driven rain displaying slightly higher RH levels at critical junctions. However, the exposure zones appear to only have a small effect on the hygrothermal performance of the build-up, as this impact is not enough to change the status of the cases from one exposure zone to another.

Effects of U-value

As expected with internal wall insulation; the higher the level of insulation, the higher the RH levels at the critical junction, due to the critical junction temperature being made colder. This shows that thermal efficiency and moisture risk management requirements conflict with each other.

In practice, the levels of insulation required in order to achieve the TER or even Part L U-value targets is unlikely to be installed since the insulation would be 'too thick' to be practically installed.

9.4. Conclusions

- High RH levels, but criteria met to relax the 80% RH threshold to 95%, which means the build-up can be considered safe (as the build-up is protected from wind-driven rain ingress, as well as using fulling vapour-open materials meaning that moisture will move more freely through the building, rather than accumulating at the critical junction to then potentially lead to fabric damage).
- As per DECC/ STBA moisture risk assessment, possibility for ‘non-perfect’ build-up in practice (ABIS conditions), which could mean possibility that sections of the cavity are bridged allowing more moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair, the risk is negligible, except in conditions of extreme driven rain.

10. Typology R11.1: Cavity masonry (uninsulated) Retrofit Measure: Internal Calcium Silicate Board Wall Insulation (IWI)

The R11.1 typology is an uninsulated cavity wall prior to retrofit. The retrofit measure is to insulate the wall internally with Calcium Silicate board insulation.

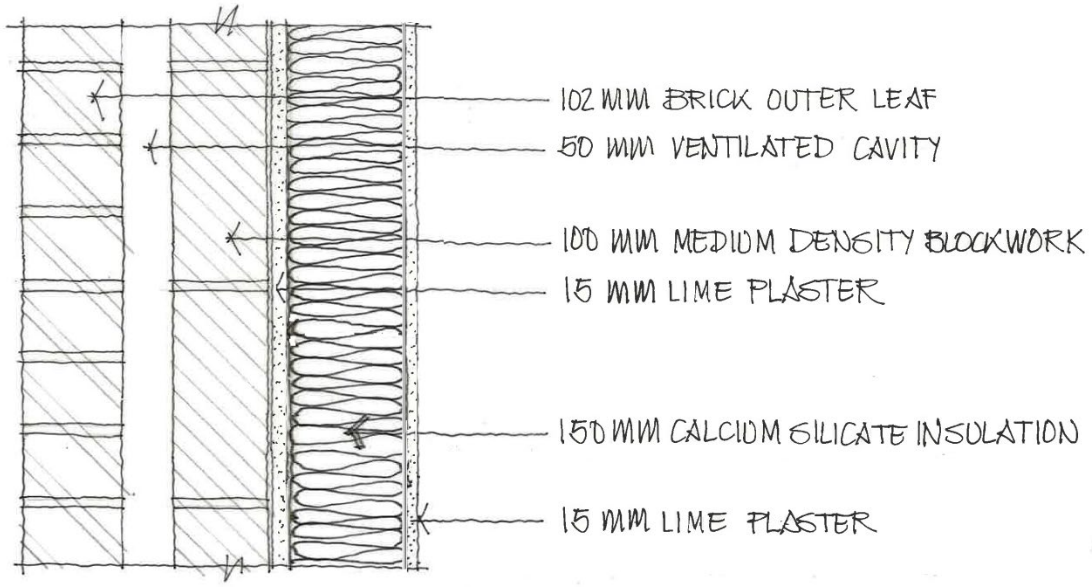


Figure 30: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

10.1. Assessment Method

As BS 5250 (2011) states in the cavity wall section (G.4.2.1), *'masonry walls of stonework, brickwork, blockwork or concrete may incorporate a cavity, the primary function of which is to prevent the transmission of rainwater to the interior. Rainwater might well penetrate the external skin of masonry, reducing its thermal resistance, and provision should be made for such moisture to drain out of the cavity.'*

To follow prescriptive guidance, the cavity is ventilated to the outside, to allow any moisture present in the cavity to be drained out. This means that the outer brick layer is considered as a 'protective cladding' and is not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the outer surface of the blockwork inner leaf to the internal finish.

As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations).

10.2. Build-up

10.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

10.2.2. Initial Conditions

Although the materials present in the pre-retrofit build-up are not exposed to wind-driven rain, the medium density blockwork is a heavy weight material, with high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

10.2.3. WUFI Build-up (post-retrofit)

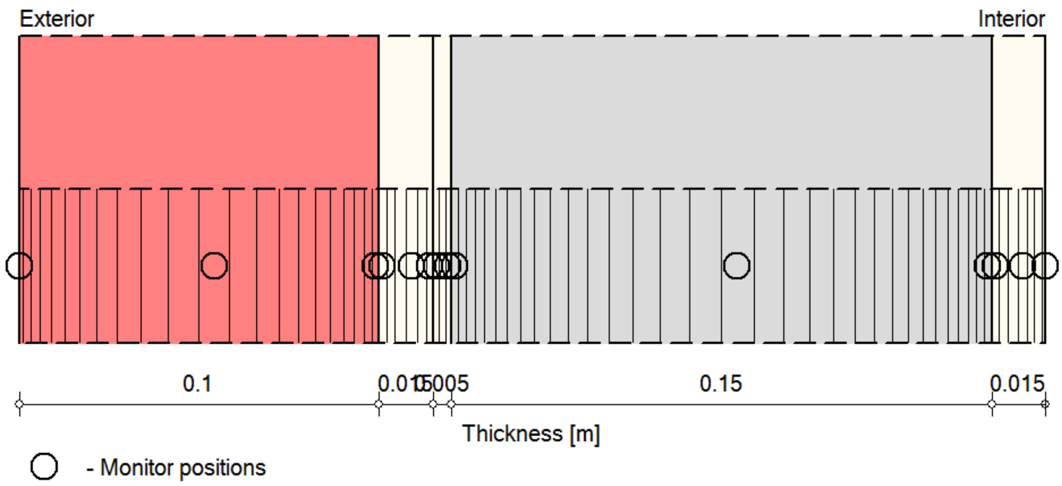
Substate:

Calcium Silicate board product installation generally requires a 'breathable' substrate on which to attach the insulation layer. Since the original build-up of this wall type has a gypsum plaster finish this is replaced with a new lime plaster along with an additional 5mm adhesive layer of the WUFI material SAKRET Klebe- und Armierungsmörtel leicht KAM-L is used both to provide a smooth surface and to help support the calcium silicate board insulation and lime plaster finish.

In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 100mm medium density blockwork inner leaf
- 15mm lime plaster (replacing original gypsum plaster)
- 5mm Adhesive layer
- 45/150/270 mm Calcium Silicate board insulation (λ = 0.055 W/m.K)
- 15mm lime plaster



Materials:

	- *Medium density blockwork (unlocked)	0.1 m
	- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m
	- SAKRET Klebe- und Armierungsmörtel leicht KAM-L	0.005 m
	- *Calcium Silikates - unlocked	0.15 m
	- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m

Figure 31 - Part L build-up used for WUFI model

WUFI Input Parameters

As the cavity is considered ventilated, both the brick outer layer and the ventilated air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the cold side of the inner leaf of blockwork) is exposed to different external conditions from exposed build-ups, due to the outer brick layer acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the outer brick layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the 'sheltered' condition in the cavity

10.3. Baseline Results

10.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the equilibrium (pre-retrofit) cases and the cases meeting the Part L target U-value, as set out below.

Table 15: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

10.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the retrofitted insulation and the plastered inner blockwork wall leaf. This is in line with BS 5250 (2011) paragraph G.4.2.4 which states that: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*.

10.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the retrofitted insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

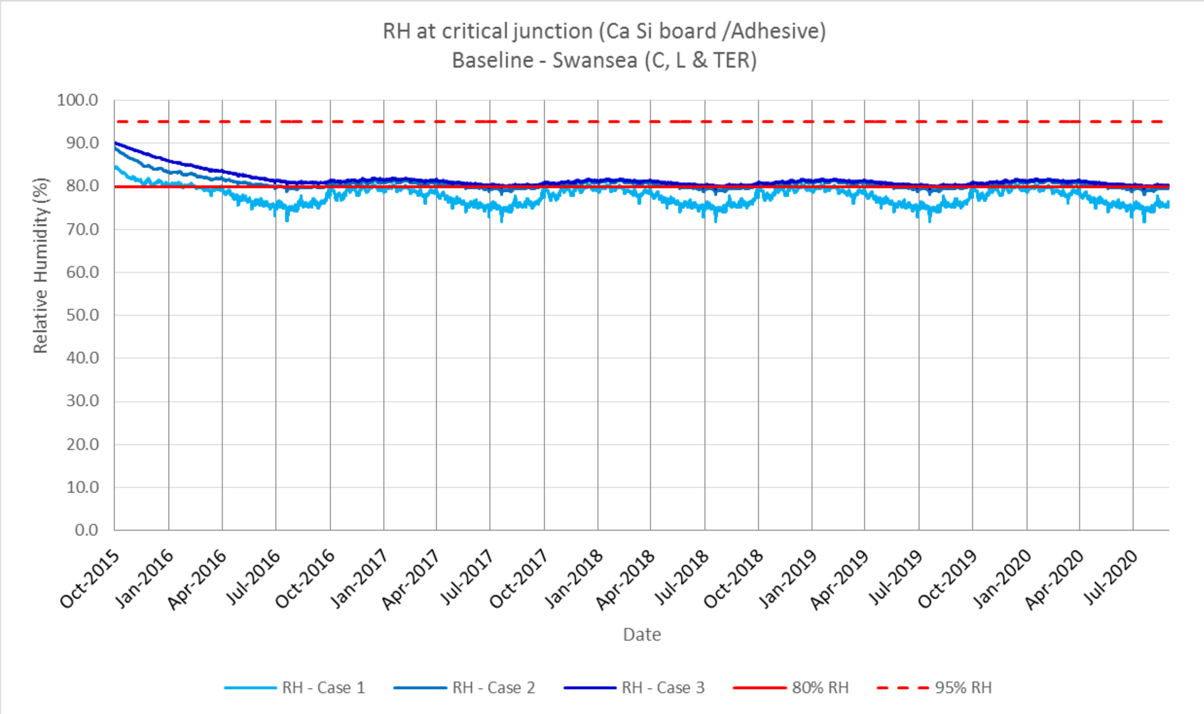


Figure 32: RH levels at critical junction for exposure zone 4

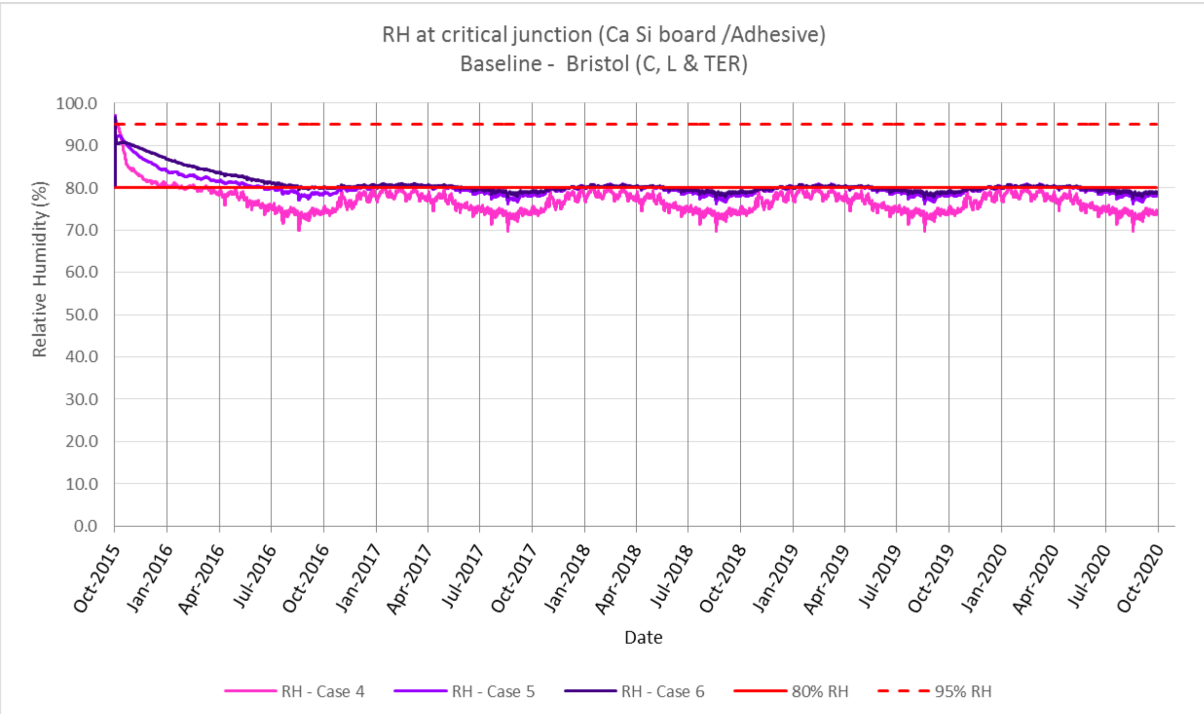


Figure 33: RH levels at critical junction for exposure zone 3

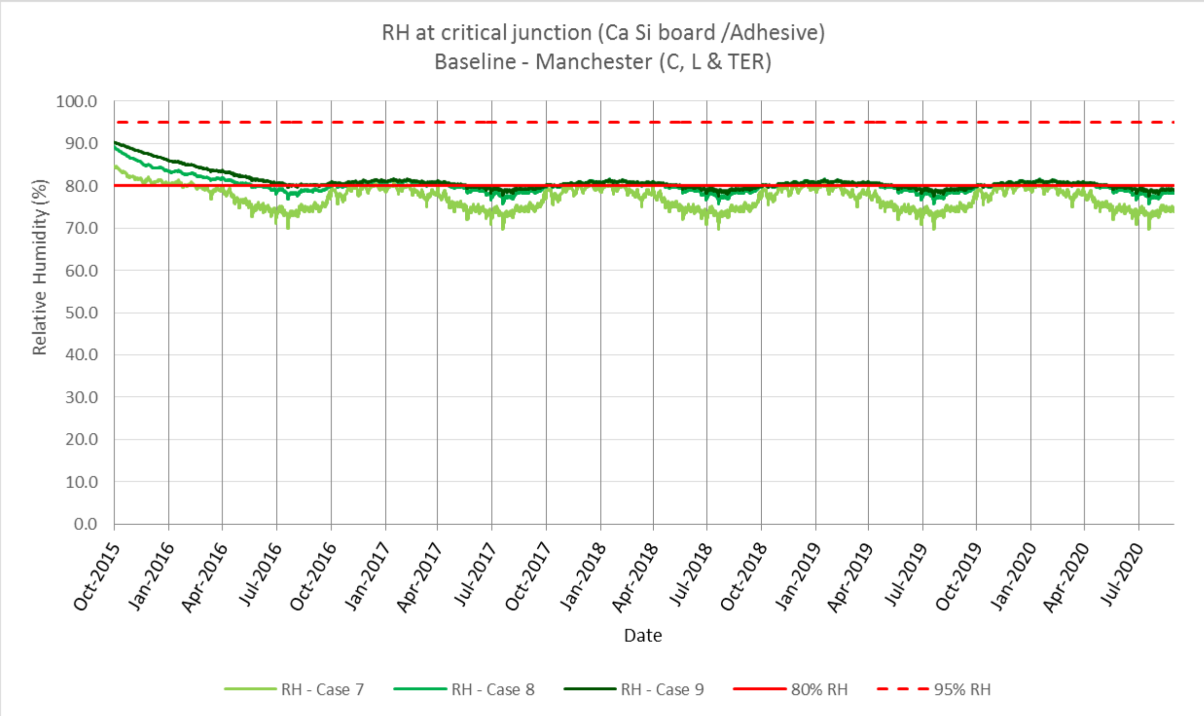


Figure 34: RH levels at critical junction for exposure zone 2

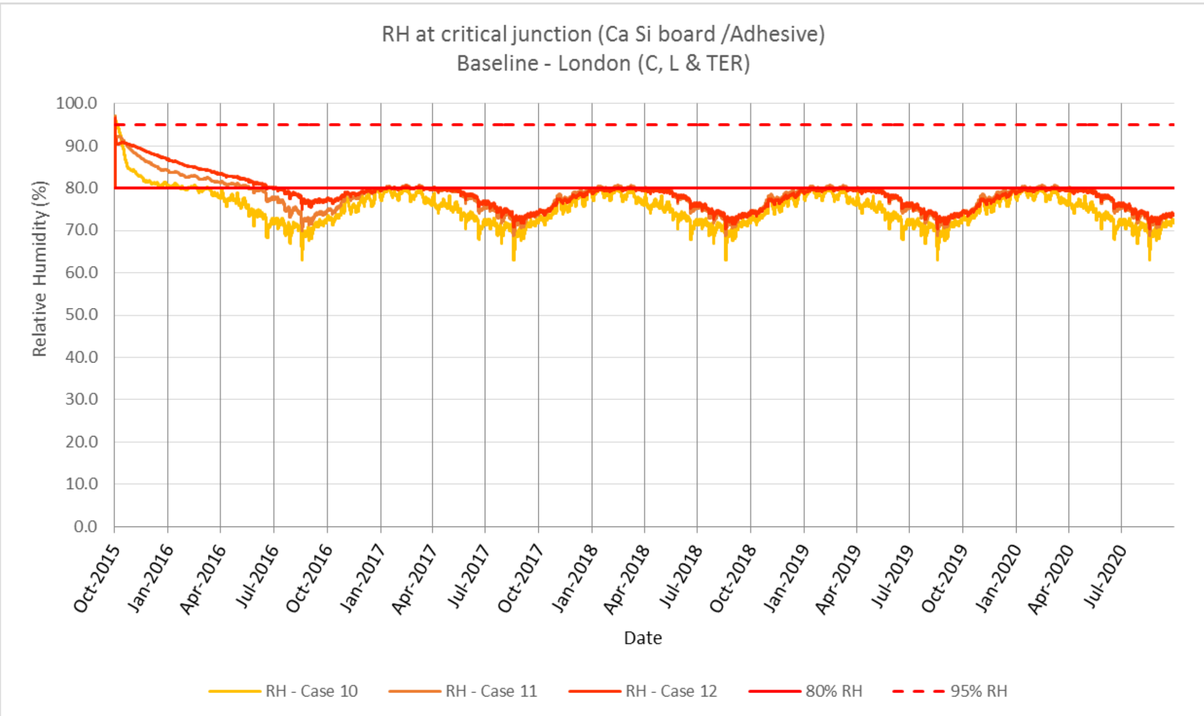


Figure 35: RH levels at critical junction for exposure zone 1

10.3.4. Results Analysis

Moisture risk assessment criteria

All scenarios achieve equilibrium. However, the first baseline case (Zone 4 - Swansea) displays RH levels above 80% throughout the year, once equilibrium is reached.

The RH levels in the cases in the lower exposure zones (exposure zones 1, 2 and 3) do not reach this critical 80% threshold only with lower levels of insulation (Part C), and zone 1 with Part L levels of insulation.

In addition all scenarios spend lengthy periods of time above the 85% RH threshold at the beginning of the modelling period. This is likely to be due to the high initial moisture levels in the lime plaster and adhesive layers.

However, the 80% RH threshold can be relaxed to 95% for this critical junction, as the build-up meets the four required criteria set out by WTA, 2009 (see section 2.3). For this reason, results showing the results based on the 95% RH threshold are also shown below.

Results

Table 16: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Risky	Pass	Pass	Pass
Part L	Fail	Risky	Risky	Pass
TER	Fail	Risky	Risky	Risky

Table 17: Summary of results with 95% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

The results comparing RH with an 85% threshold, show that, despite the build-up not being exposed to wind-driven rain, conditions suitable for interstitial mould growth can form at the critical junction in high exposure zones. However, as discussed when the RH threshold is increased to 95% the build-up can be considered 'safe; for all tested conditions.

Prescriptive guidance BS 5250 (2011), paragraph G.4.2.4, states that: *'to prevent this risk of interstitial condensation, an AVCL should be applied between the thermal insulation and the internal finish'*, although calcium silicate board installation guidance precludes this measure.

Effects of exposure zones

The effect of wind-driven rain exposure zones appears to play a role on the hygrothermal performance of the build-up, despite this build-up being considered not exposed to wind-driven rain, and this can change the status of the build-up depending on exposure zone.

Effects of U-value

In general the levels of insulation make little difference to the hygrothermal performance of each build up (within the predictable trend of greater levels of insulation having higher RH levels). However, within these relatively small differences occur at high moisture levels of around 85% creating a difference in status between these insulation levels.

10.4. Conclusions

- No need to test “construction faults” with added external moisture source as this is a likely low risk for an unfilled cavity.
- As per DECC/ STBA moisture risk assessment, possibility for ‘non-perfect’ build-up in practice (ABIS conditions), which could mean possibility that sections of the cavity are bridged allowing more moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair, the risk is negligible, except in conditions of extreme driven rain.

11. Typology R11.1: Cavity masonry (uninsulated) Retrofit Measure: Internal Sheeps Wool Wall Insulation (IWI)

The R11.1 typology is an uninsulated cavity wall prior to retrofit. The retrofit measure is to insulate the wall internally with closed-cell insulation.

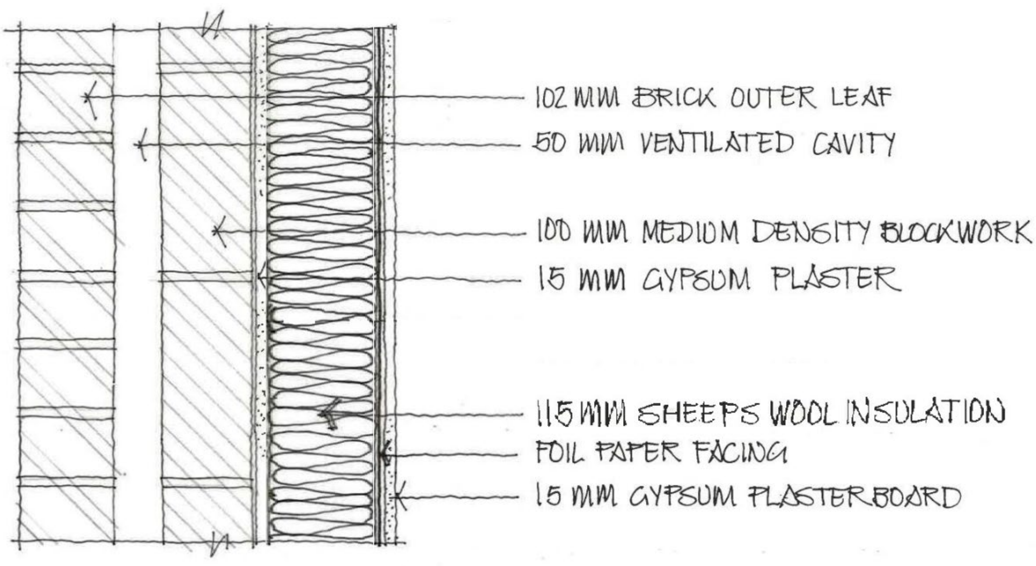


Figure 36: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

11.1. Assessment Method

As BS 5250 (2011) states in the cavity wall section (G.4.2.1), *'masonry walls of stonework, brickwork, blockwork or concrete may incorporate a cavity, the primary function of which is to prevent the transmission of rainwater to the interior. Rainwater might well penetrate the external skin of masonry, reducing its thermal resistance, and provision should be made for such moisture to drain out of the cavity.'*

To follow prescriptive guidance, the cavity is ventilated to the outside, to allow any moisture present in the cavity to be drained out. This means that the outer brick layer is considered as a 'protective cladding' and is not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the outer surface of the blockwork inner leaf to the internal finish.

As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations).

11.2. Build-up

11.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

11.2.2. Initial Conditions

Although the materials present in the pre-retrofit build-up are not exposed to wind-driven rain, the medium density blockwork is a heavy weight material, with high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

11.2.3. WUFI Build-up (post-retrofit)

Sheep's wool insulation product installations generally do not require any particular substrate on which to attach the insulation layer. The original gypsum plaster finish is therefore retained. Sheep's wool insulation is typically installed between battens and finished with a foil backed plasterboard.

In practice, it is unlikely for an internal insulation layer to exceed 100mm including finishes.

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster
- 35/115/205 mm Sheep's wool insulation (λ = 0.036 W/m.K) installed between timber battens
- 1mm foil paper facing (sd = 14m)
- 15mm gypsum plasterboard (including skim)

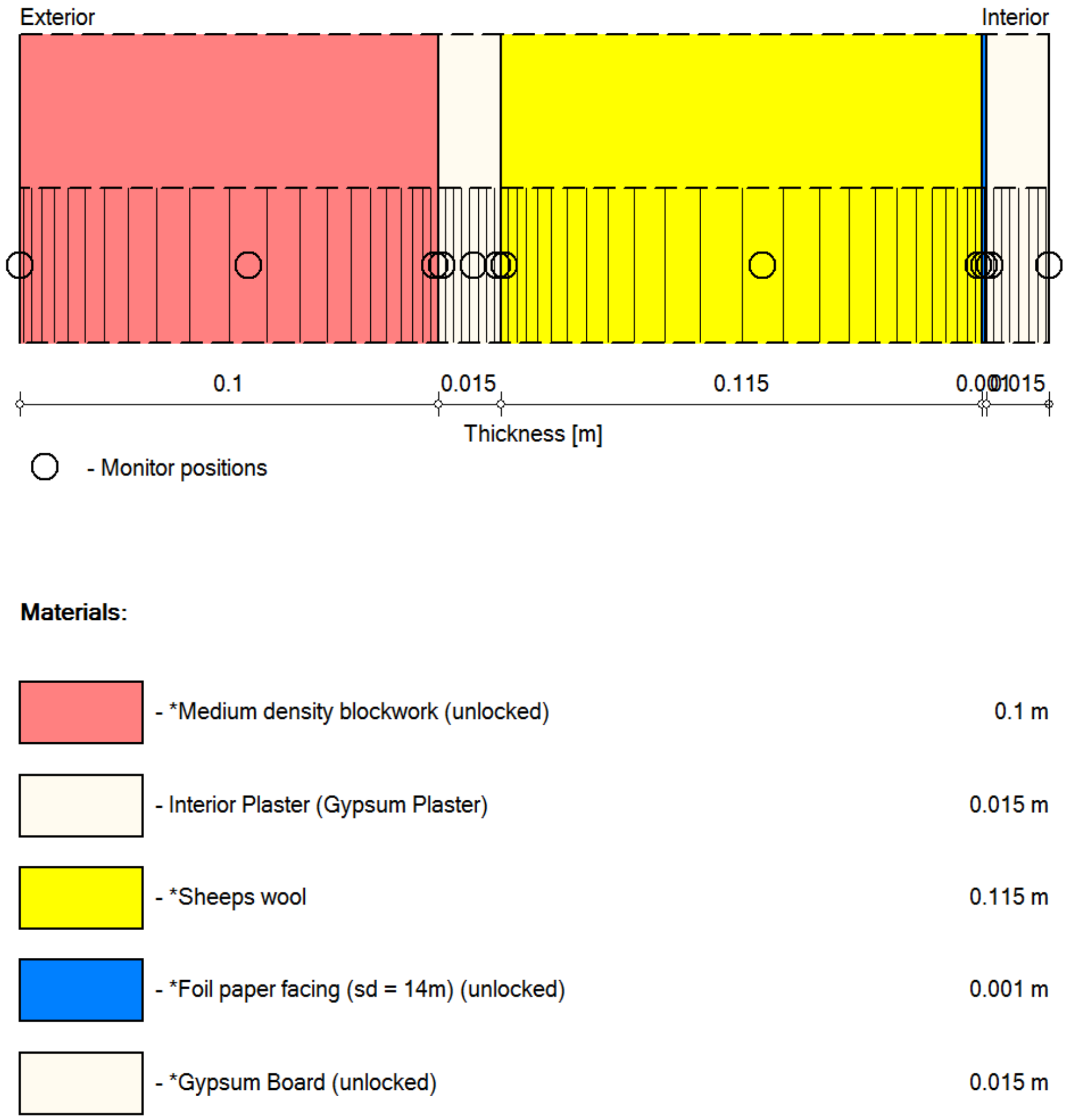


Figure 37 - Part L build-up used for WUFI model

WUFI Input Parameters

As the cavity is considered ventilated, both the brick outer layer and the ventilated air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the cold side of the inner leaf of blockwork) is exposed to different external conditions from exposed build-ups, due to the outer brick layer acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the outer brick layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the 'sheltered' condition in the cavity

11.3. Baseline Results

11.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the cases meeting the Part C, Part L and TER target U-values, as set out below.

Table 18: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

11.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the retrofitted insulation and the plastered inner blockwork wall leaf. This is in line with BS 5250 (2011) paragraph G.4.2.4 which states that: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*.

11.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the retrofitted insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

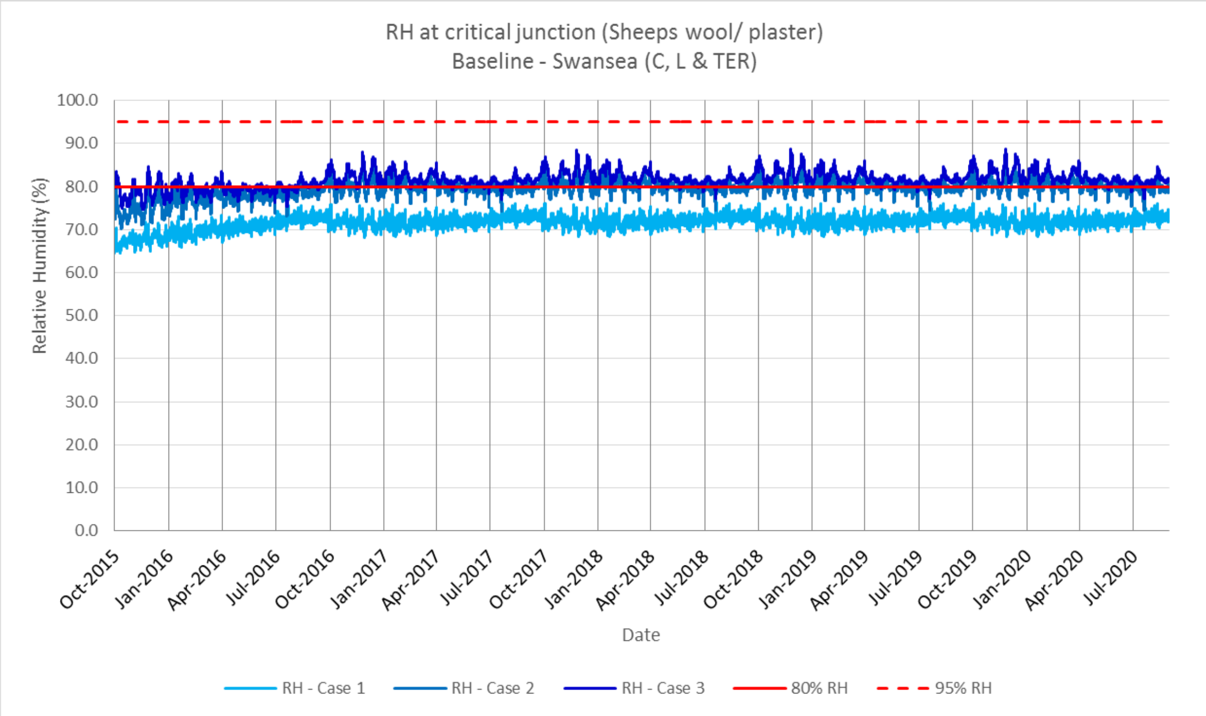


Figure 38: RH levels at critical junction for exposure zone 4

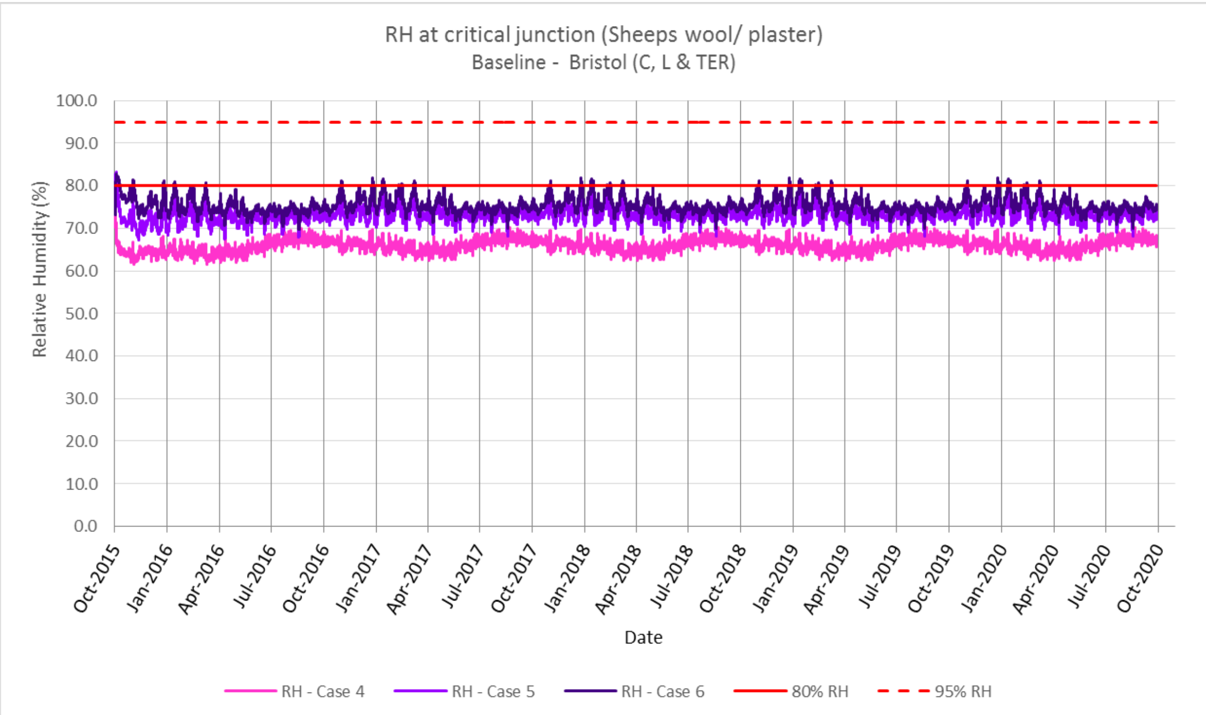


Figure 39: RH levels at critical junction for exposure zone 3

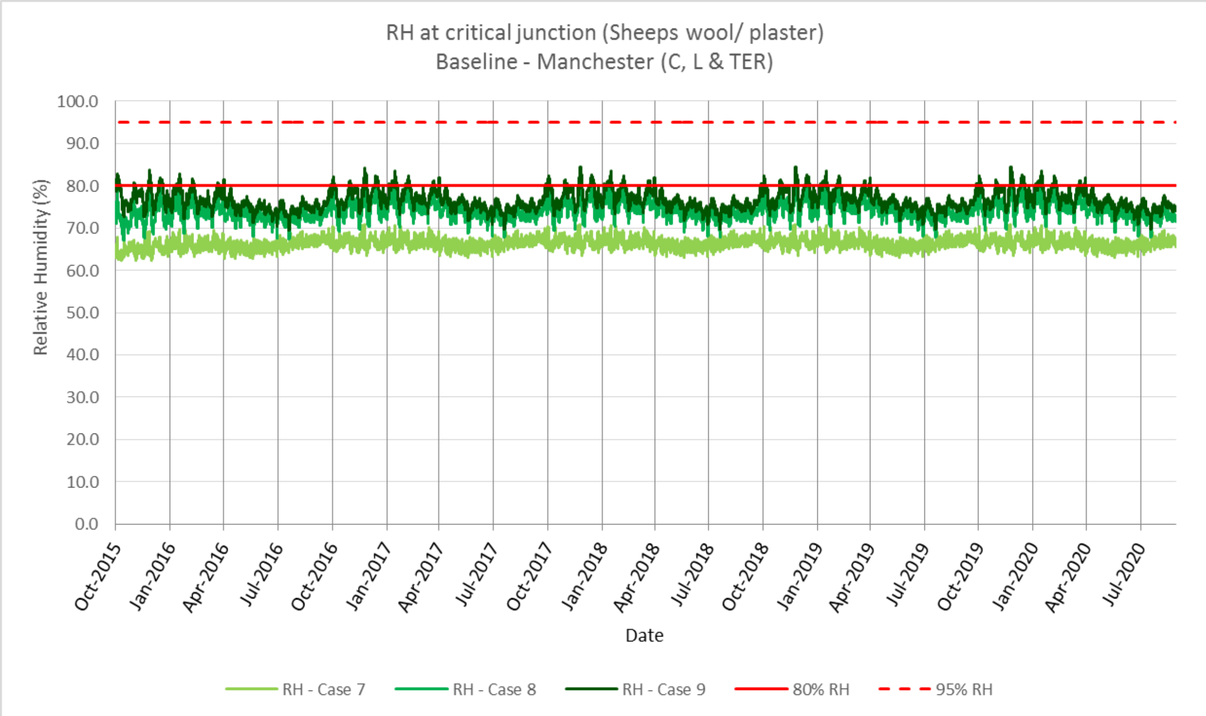


Figure 40: RH levels at critical junction for exposure zone 2

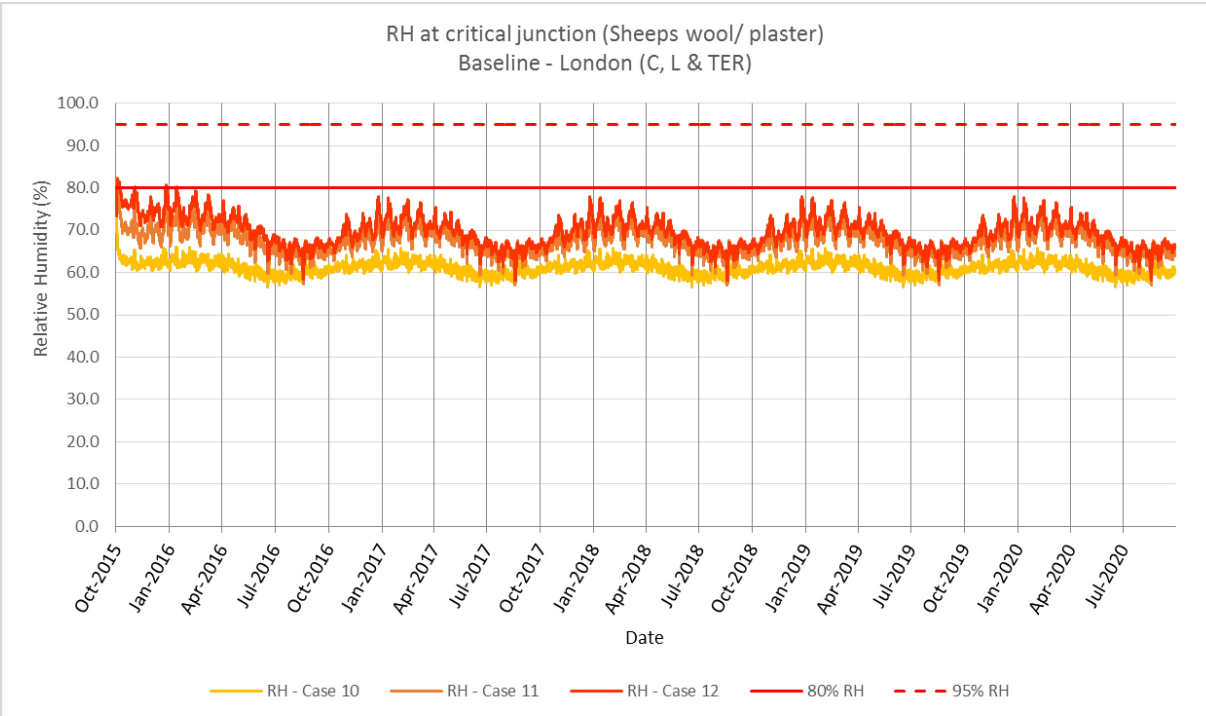


Figure 41: RH levels at critical junction for exposure zone 1

11.3.4. Results Analysis

Moisture risk assessment criteria

All scenarios achieve equilibrium. However, the part L and TER baseline cases for Zone 4 - Swansea display RH levels above 80% throughout the year. In contrast, the RH levels in the cases in the lower exposure zones (Zones 1, 2 and 3) do not reach this critical 80% threshold. So only the Zone 4 – Swansea part L and TER cases are considered as ‘fail / risky’, while the rest of the cases are considered as ‘pass’.

The 80% RH threshold can be relaxed to 95% for this critical junction, as the build-up meets the four required criteria set out by WTA, 2009 (see section 2.3). For this reason, results showing the results based on the 95% RH threshold are also shown below.

Results

Table 19: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Risky	Pass	Pass	Pass
TER	Fail	Pass	Pass	Pass

Table 20: Summary of results with 95% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

These results show that, despite the build-up not being exposed to wind-driven rain, conditions suitable for mould growth can be present at the critical junction in high exposure zones.

Effects of exposure zones

The effect of wind-driven rain exposure zones appears to play a significant role on the hygrothermal performance of the build-up, despite this build-up being considered not exposed to wind-driven rain. Indeed, the high external RH levels in the Zone 4 – Swansea weather file (higher than in other exposure zones) are sufficient to change the status of the build-up from ‘safe’ to ‘Risky / fail’ for greater levels of insulation.

Effects of U-value

Although the Part C levels of insulation result in noticeably lower RH levels than either the Part C or TER levels of insulation it can be observed that at higher levels of insulation this effect is diminished considerably.

It should be noted however that the levels of insulation required in order to achieve the U-value targets is unlikely to be installed in practice since the insulation would be 'too thick' to be practical.

11.4. Conclusions

- Exposure zones have an impact as higher exposure zones have worse performance.
- Build-up ‘safe’ in most cases, except in extreme exposure zone (Zone 4).
- As per DECC/ STBA moisture risk assessment, possibility for ‘non-perfect’ build-up in practice (ABIS conditions), which could mean possibility that sections of the cavity are bridged allowing more moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair, the risk is negligible, except in conditions of extreme driven rain.

12. Typology R11.3: Partial-fill cavity masonry Retrofit Measure: Internal Wood Fibre Wall Insulation (IWI)

The R11.3 typology is a cavity wall with partial-fill insulation and a semi-porous finish (e.g. facing brickwork) prior to retrofit. The retrofit measure is to add wood fibre internal wall insulation (IWI).

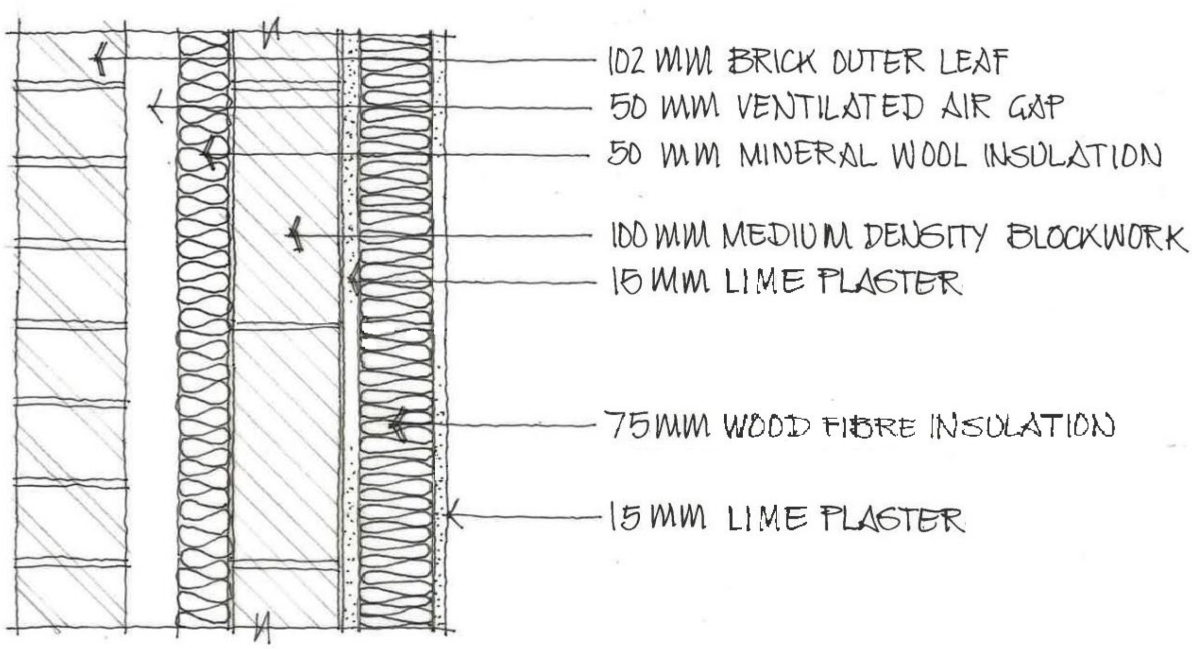


Figure 42: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

12.1. Assessment Method

As BS 5250 (2011) states in the cavity wall section (paragraph G.4.2.1), *'masonry walls of stonework, brickwork, blockwork or concrete may incorporate a cavity, the primary function of which is to prevent the transmission of rainwater to the interior. Rainwater might well penetrate the external skin of masonry, reducing its thermal resistance, and provision should be made for such moisture to drain out of the cavity.'*

To follow prescriptive guidance, the cavity is ventilated to the outside, to allow any moisture present in the cavity to be drained out. This means that the outer brick layer is considered as a 'protective cladding' and is not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the outer surface of the cavity wall insulation to the internal finish.

As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations).

12.2. Build-up

12.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 50mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

12.2.2. Initial Conditions

Although the materials present in the pre-retrofit build-up are not exposed to wind-driven rain, the medium density blockwork is a heavy weight material, with high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

12.2.3. WUFI Build-up (post-retrofit)

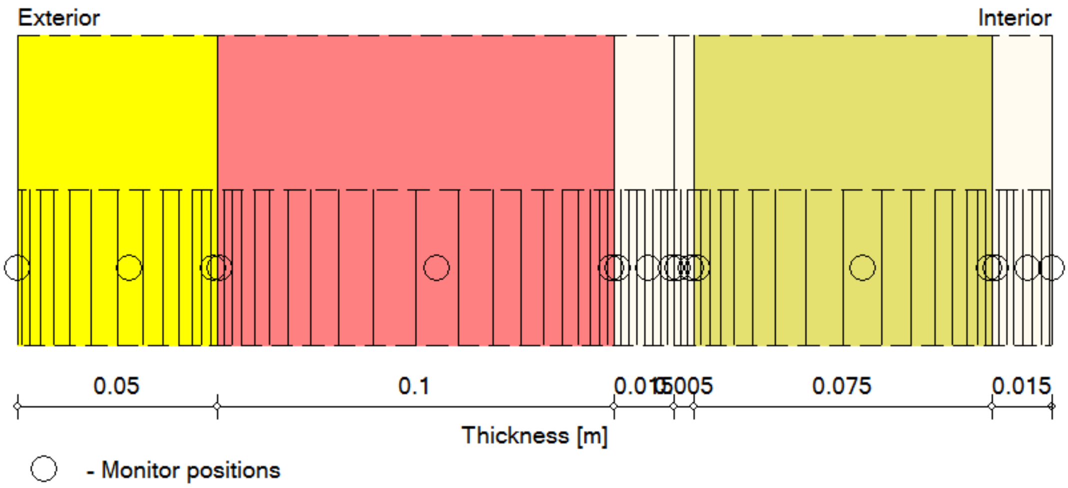
Wood fibre insulation product installation generally requires a 'breathable' substrate on which to attach the insulation layer. Since the original build-up of this wall type has a gypsum plaster finish this is replaced with a new lime plaster along with an additional 5mm 'adhesive' layer with hygrothermal properties similar to that of lime plaster is used both to provide a smooth surface and to help support the wood fibre insulation and lime plaster finish.

In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Since the wall is already insulated beyond the Part C U-value target a nominal 25mm insulation is modelled in lieu of a Part C compliant build-up.

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 50mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm lime plaster (replacing original gypsum plaster)
- 5mm lime plaster (as adhesive)
- 25/75/200 mm Wood fibre insulation (λ = 0.045 W/mK)
- 15mm lime plaster



Materials:

- Mineral Wool (heat cond.: 0,04 W/mK)	0.05 m
- *Medium density blockwork (unlocked)	0.1 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.005 m
- *Generic Wood Fibre - unlocked	0.075 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m

Figure 43 - Part L build-up used for WUFI model

WUFI Input Parameters

As the cavity is considered ventilated, both the brick outer layer and the ventilated air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the cold side of the insulation) is exposed to different external conditions from exposed build-ups, due to the outer brick layer acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the outer brick layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the 'sheltered' condition in the cavity

12.3. Baseline Results

12.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the cases meeting the Part C, Part L and TER target U-values, as set out below.

Table 21: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

12.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the existing plastered inner blockwork wall leaf and the retrofitted internal wall insulation. This is in line with BS 5250 (2011) paragraph G.4.2.4 which states that: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*.

12.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the retrofitted internal wall insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

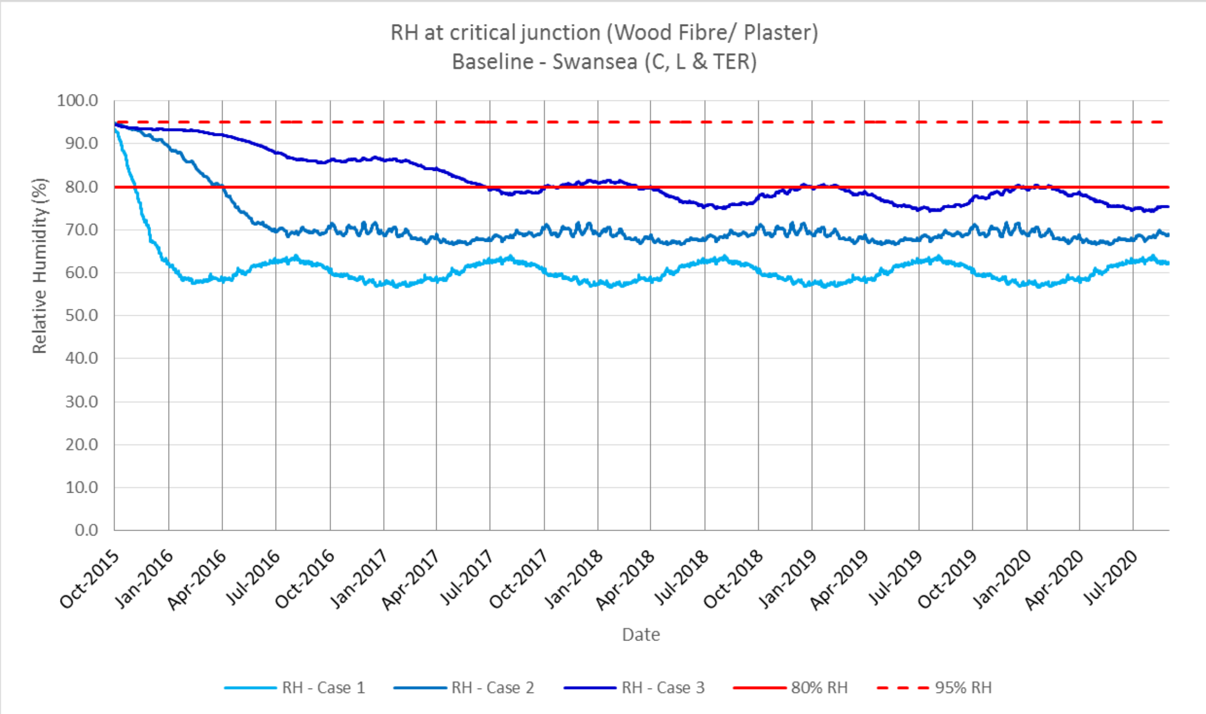


Figure 44: RH levels at critical junction for exposure zone 4

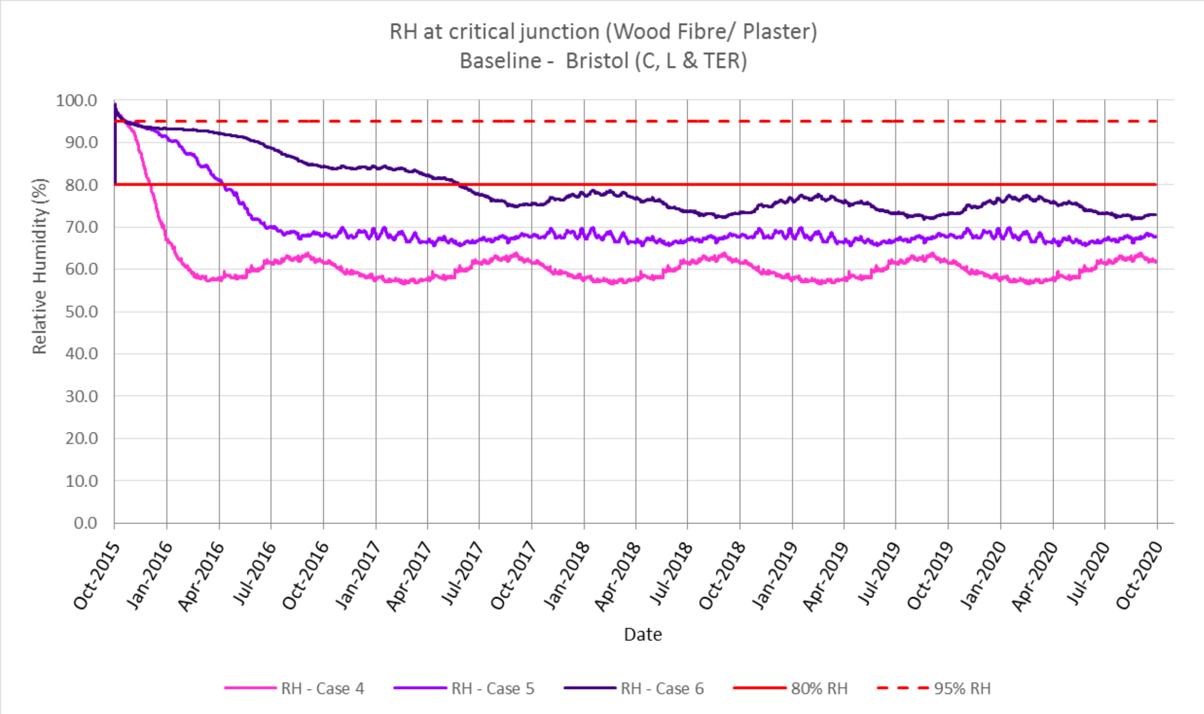


Figure 45: RH levels at critical junction exposure zone 3

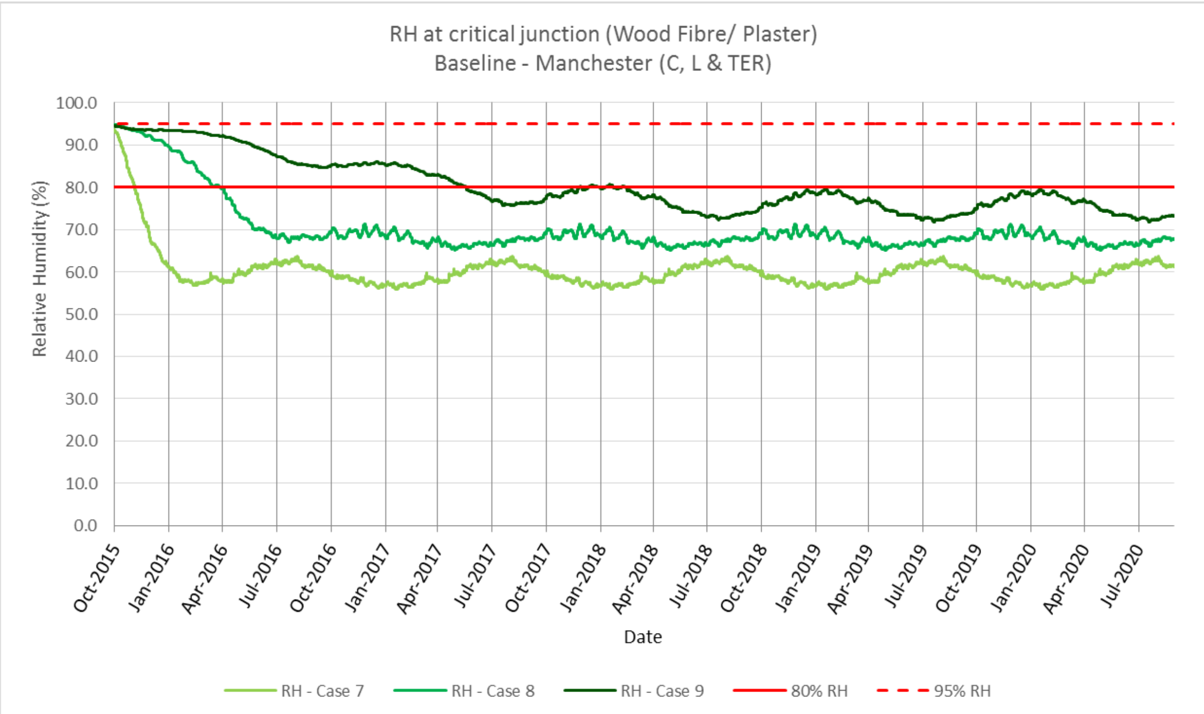


Figure 46: RH levels at critical junction for exposure zone 2

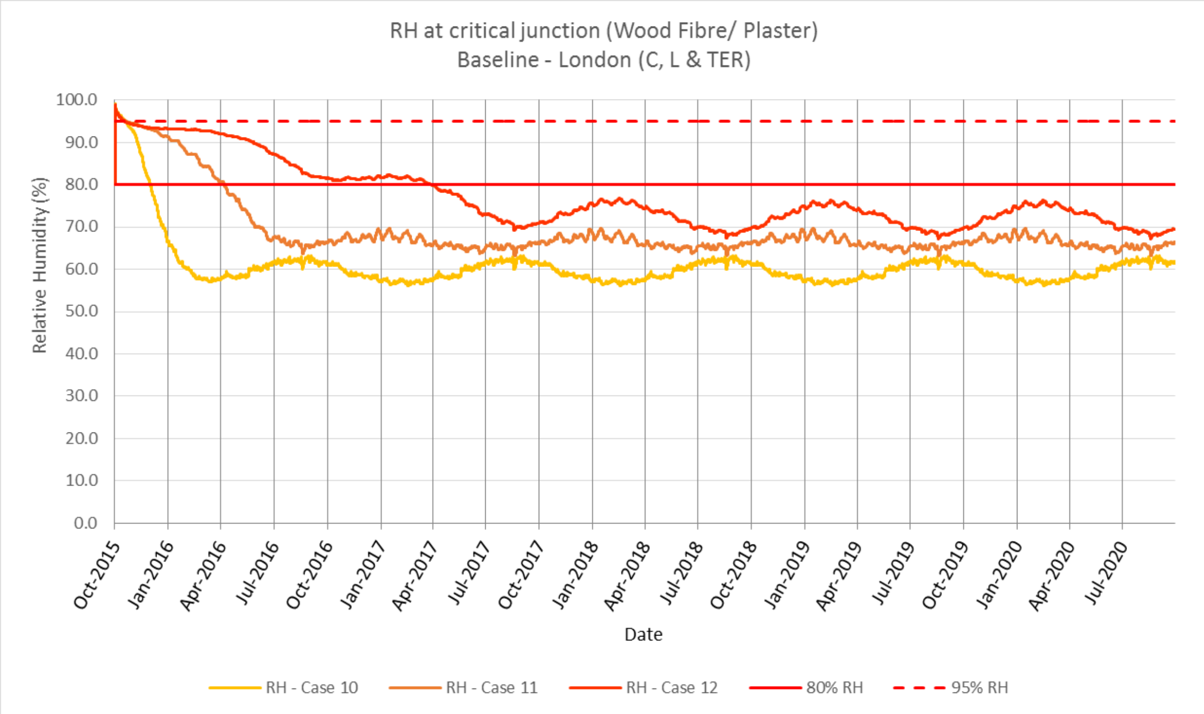


Figure 47: RH levels at critical junction for exposure zone 1

12.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>

All scenarios reach equilibrium, do not accumulate moisture over time and have RH levels well below 80%. However, all scenarios spend lengthy periods of time initially above the 80% RH threshold at the beginning of the modelling period. This is likely to be due to the high initial moisture levels in the lime plaster and adhesive layers.

However, the 80% RH threshold can be relaxed to 95% for this critical junction, as the build-up meets the four required criteria set out by WTA, 2009 (see section 2.3). For this reason, results showing the results based on the 95% RH threshold are also shown below.

Results

Table 22: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	Swansea (Zone 4)	Bristol (Zone 3)	Manchester (Zone 2)	London (Zone 1)
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Fail	Fail	Fail	Fail

Table 23: Summary of results with 95% RH threshold

	Exposure Zones			
Target U-values	Swansea (Zone 4)	Bristol (Zone 3)	Manchester (Zone 2)	London (Zone 1)
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

Effects of exposure zones

The effect of wind-driven rain exposure zones is visible on the graphs – with lower average RH levels in less exposed zones. This is directly due to different external (and consequently internal) conditions. However, this small difference in exposure zones does not alter the status of each case.

Effects of U-value

The most noticeable effect of increasing insulation levels is to shift the peak RH from summer to winter. This tendency is useful since although there are higher peak RH levels for higher levels of insulation , the temperature at this time should be insufficient to encourage mould growth.

12.3.5. Additional Monitored Junction

The critical junction is correctly located in BS 5250 (2011), being the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation.

BS 5250 (2011) also identifies a second interface for cavity walls, which is less at risk but where there might still be a risk for moisture to accumulate, stating: "*Any interstitial condensation which might occur will do so on the inner surface of the external skin, where it is unlikely to cause damage to non-hygroscopic insulation, or insulation which does not fill the cavity.*"

This second interface is not present in the WUFI model, so the monitor closest to the outer surface of the mineral wool cavity wall insulation is shown.

The chart show both the exposure zone 4 TER case and the exposure zone 1 part C case to illustrate the extreme cases within the modelling regime.

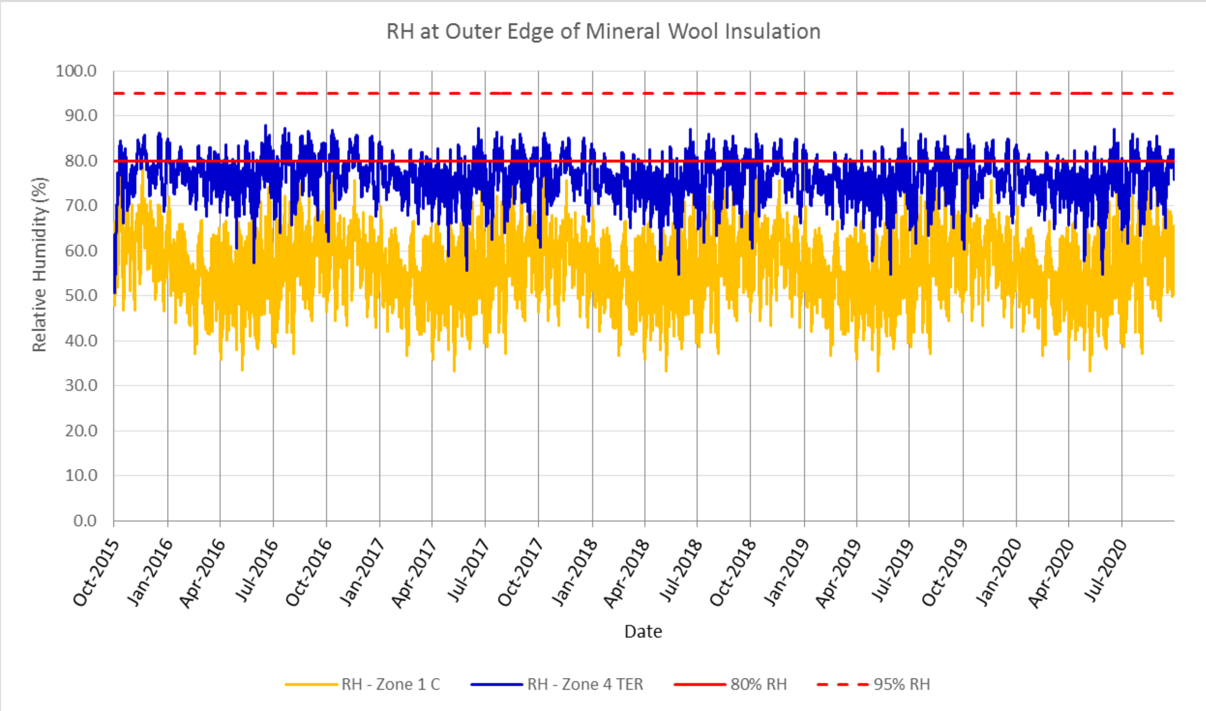


Figure 48: RH levels at additional monitored junction

This result is in line with the previous findings from the M7 report, and confirms the previous results. Each case reaches equilibrium, does not accumulate moisture over time, or reach saturation levels of moisture (condensation) with RH levels well below 80% for much or all of the time.

12.4. Conclusions

- Build-up sheltered from the elements and moisture-open so theoretically safe.
- Exposure zones have some impact.
- As per DECC/ STBA moisture risk assessment. Possibility for ‘non-perfect’ build-up in practice (ABIS conditions), which could mean possibility that sections of the cavity are bridged allowing more moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair, the risk is negligible, except in conditions of extreme driven rain.

13. Typology R11.3: Partial-fill cavity masonry Retrofit Measure: Internal Calcium Silicate Board Wall Insulation (IWI)

The R11.3 typology is a cavity wall with partial-fill insulation and a semi-porous finish (e.g. facing brickwork) prior to retrofit. The retrofit measure is to add internal wall insulation (IWI).

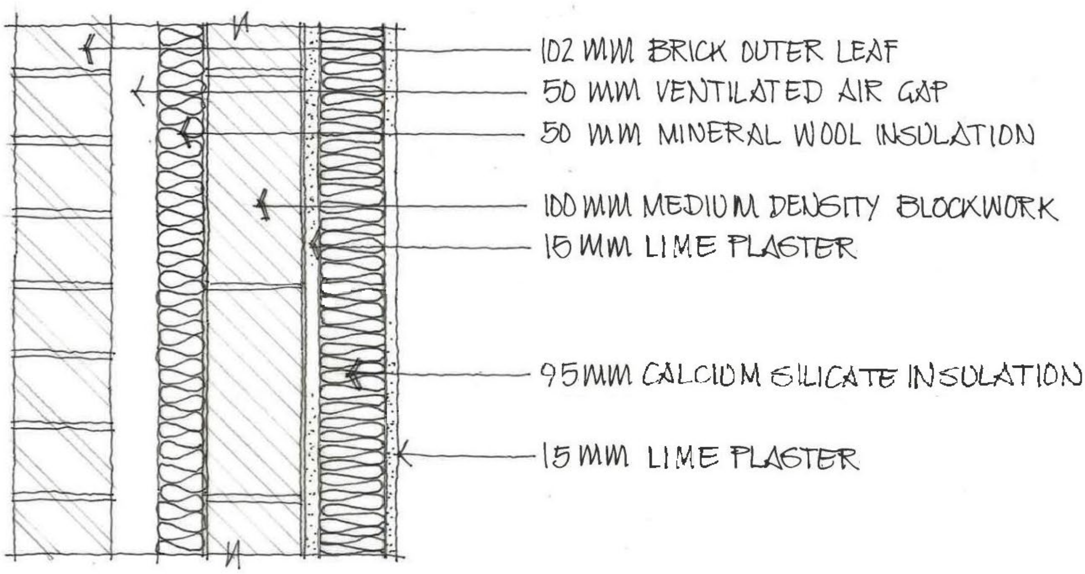


Figure 49: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

13.1. Assessment Method

As BS 5250 (2011) states in the cavity wall section (paragraph G.4.2.1), *'masonry walls of stonework, brickwork, blockwork or concrete may incorporate a cavity, the primary function of which is to prevent the transmission of rainwater to the interior. Rainwater might well penetrate the external skin of masonry, reducing its thermal resistance, and provision should be made for such moisture to drain out of the cavity.'*

To follow prescriptive guidance, the cavity is ventilated to the outside, to allow any moisture present in the cavity to be drained out. This means that the outer brick layer is considered as a 'protective cladding' and is not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the outer surface of the cavity wall insulation to the internal finish.

As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations).

13.2. Build-up

13.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 50mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

13.2.2. Initial Conditions

Although the materials present in the pre-retrofit build-up are not exposed to wind-driven rain, the medium density blockwork is a heavy weight material, with high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

13.2.3. WUFI Build-up (post-retrofit)

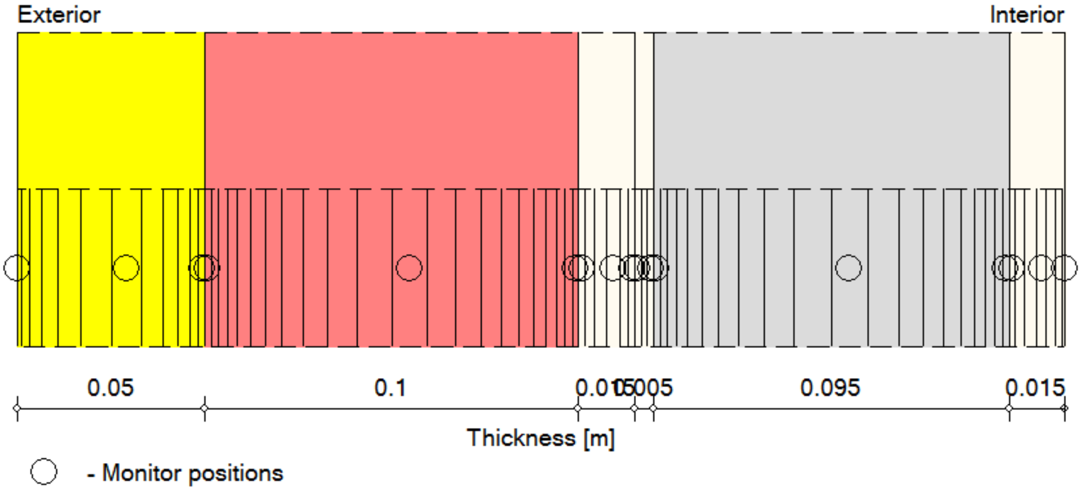
Calcium Silicate board product installation generally requires a 'breathable' substrate on which to attach the insulation layer. Since the original build-up of this wall type has a gypsum plaster finish this is replaced with a new lime plaster along with an additional 5mm adhesive layer of the WUFI material SAKRET Klebe- und Armierungsmörtel leicht KAM-L is used both to provide a smooth surface and to help support the wood fibre insulation and lime plaster finish.

In practice, it is unlikely for an internal insulation layer to exceed 100mm including finishes.

Since the wall is already insulated beyond the Part C U-value target a nominal 25mm insulation is modelled in lieu of a Part C compliant build-up.

<u>Build-Up:</u>

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 50mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm lime plaster
- 5mm Adhesive layer
- 25/95/240 mm Calcium Silicate Board insulation (λ = 0.055 W/m.K) (25mm is nominal as pre-retrofit wall already exceeds the Part C requirement)
- 15mm lime plaster



Materials:

- Mineral Wool (heat cond.: 0,04 W/mK)	0.05 m
- *Medium density blockwork (unlocked)	0.1 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.005 m
- *Calcium Silikates - unlocked	0.095 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m

Figure 50 - Part L build-up used for WUFI model

WUFI Input Parameters

As the cavity is considered ventilated, both the brick outer layer and the ventilated air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the cold side of the insulation) is exposed to different external conditions from exposed build-ups, due to the outer brick layer acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the outer brick layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the 'sheltered' condition in the cavity

13.3. Baseline Results

13.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the equilibrium (pre-retrofit) cases and the cases meeting the Part L target U-value, as set out below.

Table 24: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

13.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the existing plastered inner blockwork wall leaf and the retrofitted internal wall insulation. This is in line with BS 5250 (2011) paragraph G.4.2.4 which states that: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*.

13.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the retrofitted internal wall insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

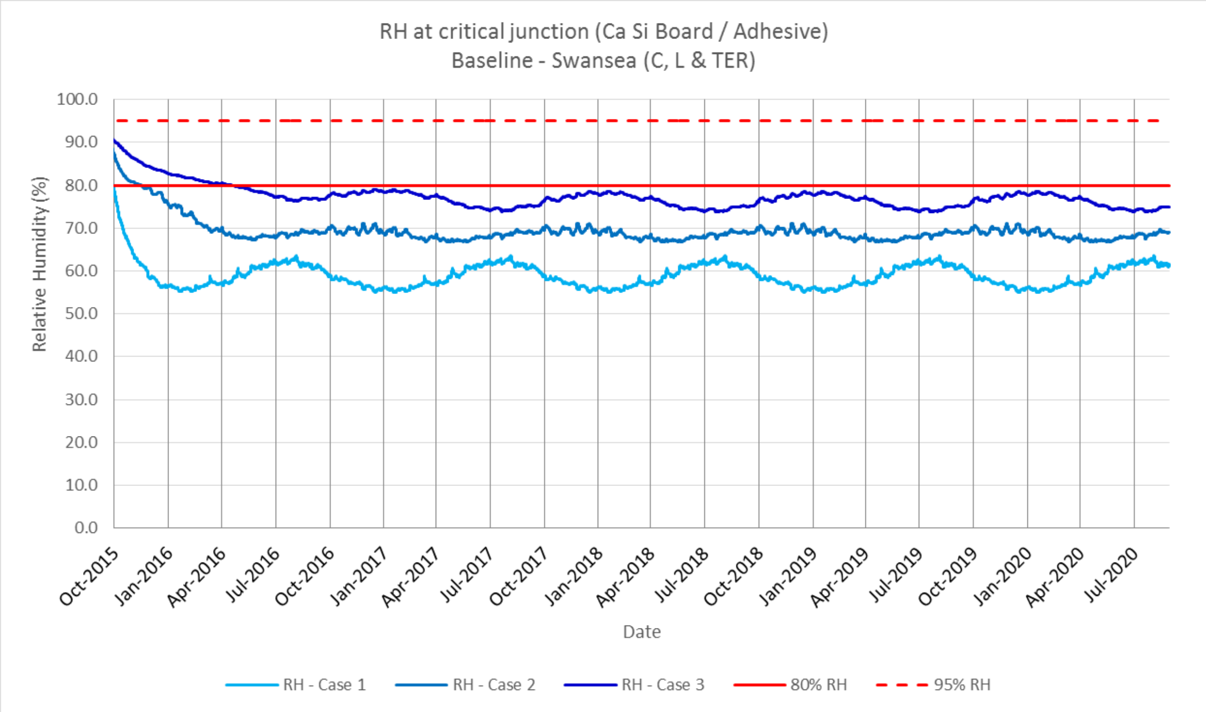


Figure 51: RH levels at critical junction for exposure zone 4

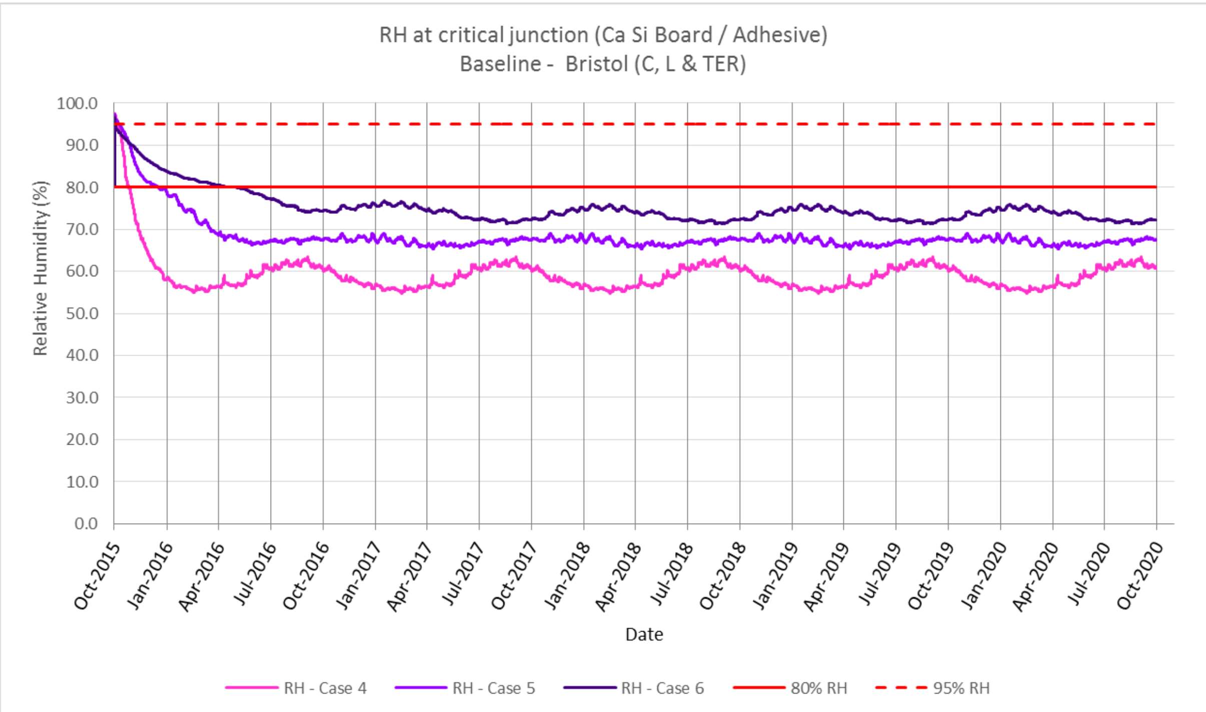


Figure 52: RH levels at critical junction for exposure zone 3

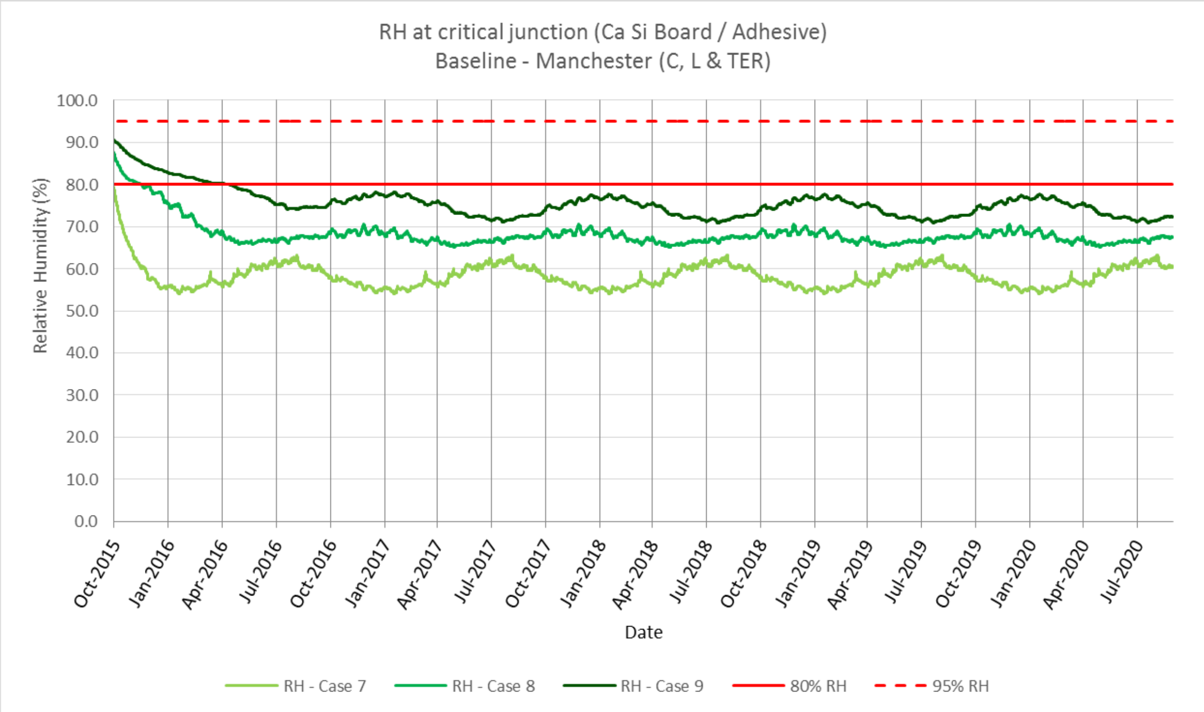


Figure 53: RH levels at critical junction for exposure zone 2

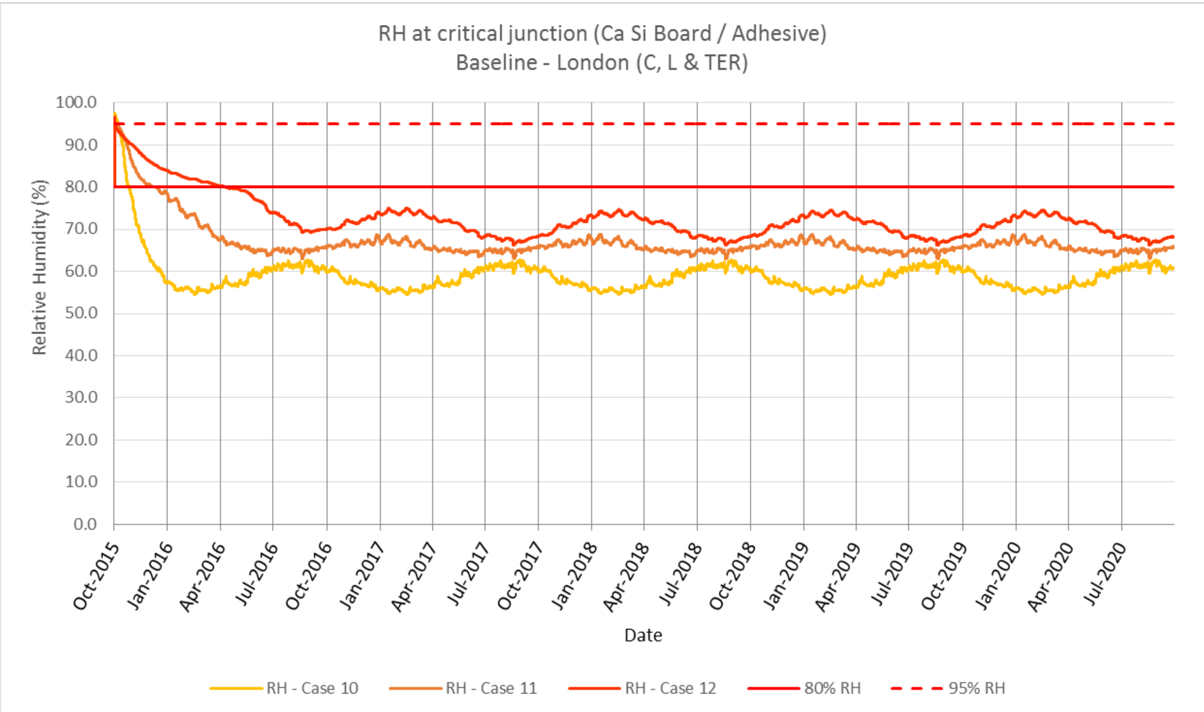


Figure 54: RH levels at critical junction for exposure zone 1

13.3.4. Results Analysis

Moisture risk assessment criteria

All scenarios can be considered to 'pass' as they all reach equilibrium, do not accumulate moisture over time and have RH levels well below 80%. However, all scenarios spend lengthy periods of time initially above the 80% RH threshold at the beginning of the modelling period. This is likely to be due to the high initial moisture levels in the lime plaster and adhesive layers.

In addition, the 80% RH threshold can be relaxed to 95% for this critical junction, as the build-up meets the four required criteria set out by WTA, 2009 (see section 2.3). For this reason, results showing the results based on the 95% RH threshold are also shown below.

Results

Table 25: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

Table 26: Summary of results with 95% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

Effects of exposure zones

The effect of wind-driven rain exposure zones is visible on the graphs – with lower average RH levels in less exposed zones. This is directly due to different external (and consequently internal) conditions. However, this small difference in exposure zones does not alter the status of each case.

Effects of U-value

The most noticeable effect of increasing insulation levels is to shift the peak RH from summer to winter. This tendency is useful since although there are higher peak RH levels for higher levels of insulation , the temperature at this time should be insufficient to encourage mould growth.

13.3.5. Additional Monitored Junction

The critical junction is correctly located in BS 5250 (2011), being the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation.

BS 5250 (2011) also identifies a second interface for cavity walls, which is less at risk but where there might still be a risk for moisture to accumulate, stating: "*Any interstitial condensation which might occur will do so on the inner surface of the external skin, where it is unlikely to cause damage to non-hygroscopic insulation, or insulation which does not fill the cavity."*

This second interface is not present in the WUFI model, so the monitor closest to the outer surface of the mineral wool cavity wall insulation has been checked.

The results are similar to the same monitored junctions for R11.3 with Wood Fibre IWI and this result is in line with the previous findings from the M7 report, and confirms the previous results. Each case reaches equilibrium, does not accumulate moisture over time, or reach saturation levels of moisture (condensation) with RH levels well below 80% for much or all of the time.

13.4. Conclusions

- Build-up sheltered from the elements and moisture-open so theoretically safe.
- Safe results similar to M7 BS EN ISO 13788 calculations.
- Exposure zones have little impact.
- As per DECC/ STBA moisture risk assessment. Possibility for 'non-perfect' build-up in practice (ABIS conditions), which could mean possibility that sections of the cavity are bridged allowing more moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair, the risk is negligible, except in conditions of extreme driven rain.

14. Typology R11.3: Partial-fill cavity masonry Retrofit Measure: Internal Sheep's Wool Wall Insulation (IWI)

The R11.3 typology is a cavity wall with partial-fill insulation and a semi-porous finish (e.g. facing brickwork) prior to retrofit. The retrofit measure is to add internal sheep's wool wall insulation (IWI).

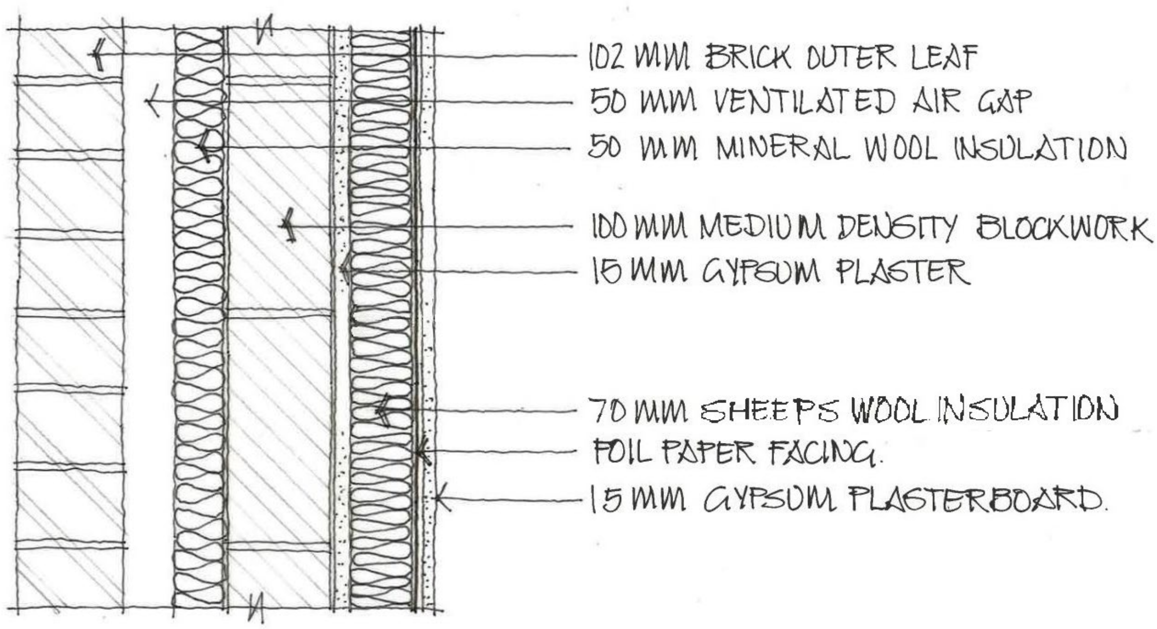


Figure 55: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

14.1. Assessment Method

As BS 5250 (2011) states in the cavity wall section (paragraph G.4.2.1), *‘masonry walls of stonework, brickwork, blockwork or concrete may incorporate a cavity, the primary function of which is to prevent the transmission of rainwater to the interior. Rainwater might well penetrate the external skin of masonry, reducing its thermal resistance, and provision should be made for such moisture to drain out of the cavity.’*

To follow prescriptive guidance, the cavity is ventilated to the outside, to allow any moisture present in the cavity to be drained out. This means that the outer brick layer is considered as a ‘protective cladding’ and is not technically part of the ‘thermal’ build-up. As shown in the following section, the modelled build-up therefore only extends from the outer surface of the cavity wall insulation to the internal finish.

As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations).

14.2. Build-up

14.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 50mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

14.2.2. Initial Conditions

Although the materials present in the pre-retrofit build-up are not exposed to wind-driven rain, the medium density blockwork is a heavy weight material, with high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

14.2.3. WUFI Build-up (post-retrofit)

Sheep's wool insulation product installations generally do not require any particular substrate on which to attach the insulation layer. The original gypsum plaster finish is therefore retained. Sheep's wool insulation is typically installed between battens and finished with a foil backed plasterboard.

In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Since the wall is already insulated beyond the Part C U-value target a nominal 25mm insulation is modelled in lieu of a Part C compliant build-up.

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 50mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster
- 25/70/180 mm Sheeps wool insulation (λ = 0.036 W/m.K) installed between timber battens
- 1mm foil paper facing (sd = 14m)
- 15mm gypsum plasterboard (including skim)

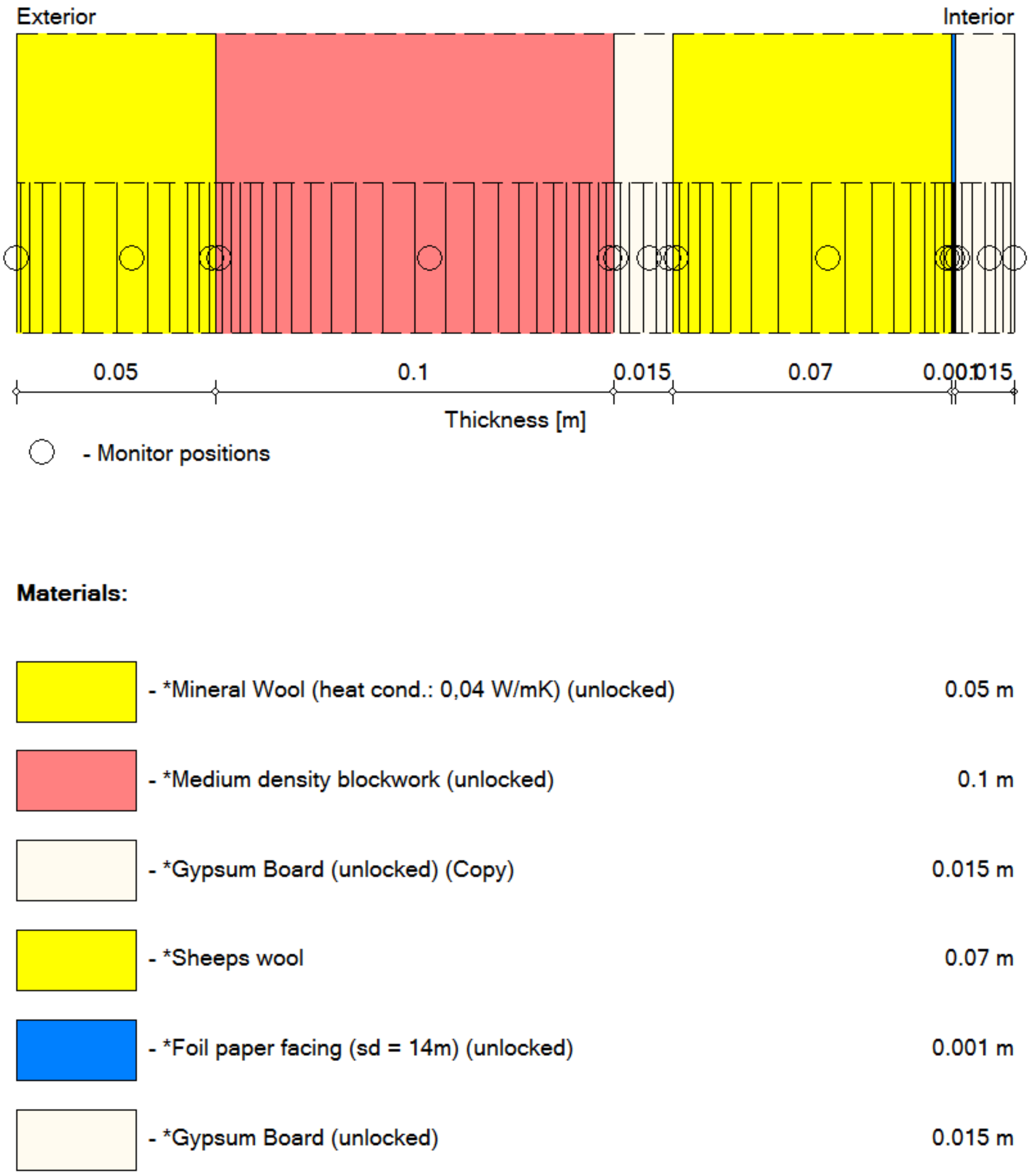


Figure 56 - Part L build-up used for WUFI model

WUFI Input Parameters

As the cavity is considered ventilated, both the brick outer layer and the ventilated air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the cold side of the insulation) is exposed to different external conditions from exposed build-ups, due to the outer brick layer acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the outer brick layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the 'sheltered' condition in the cavity

14.3. Baseline Results

14.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the cases meeting the Part C, Part L and TER target U-values, as set out below.

Table 27: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

14.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the existing plastered inner blockwork wall leaf and the retrofitted internal wall insulation. This is in line with BS 5250 (2011) paragraph G.4.2.4 which states that: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*.

14.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the retrofitted internal wall insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

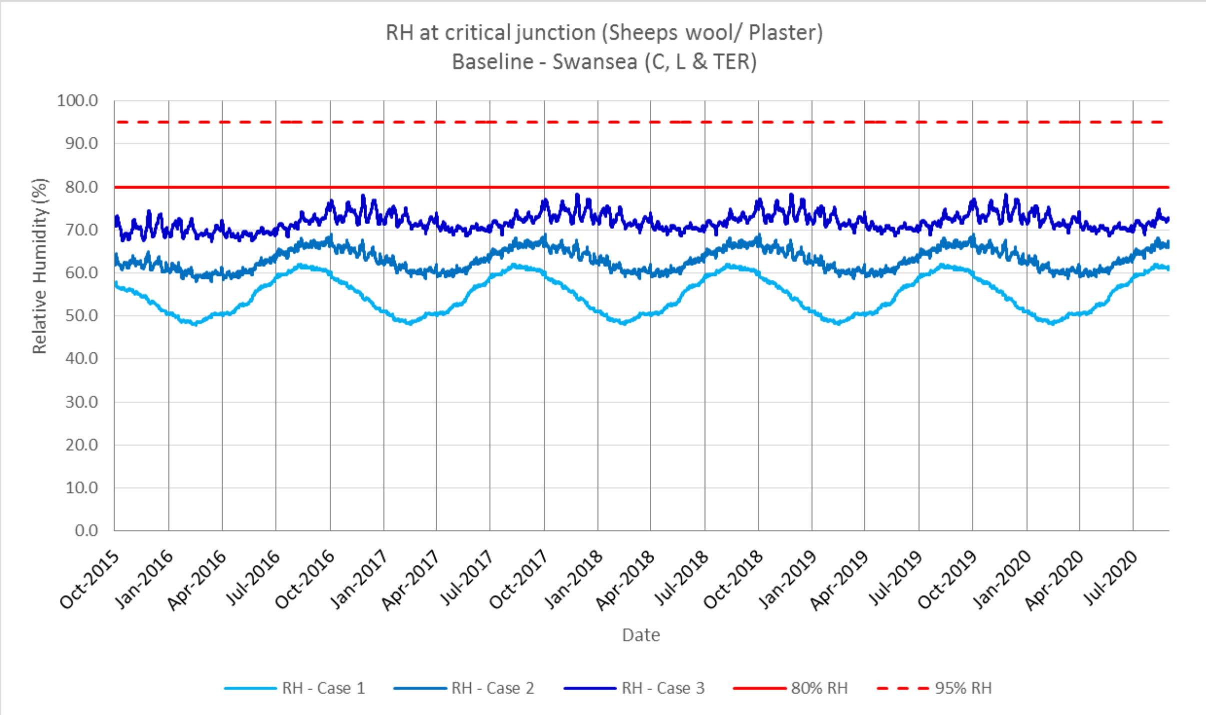


Figure 57: RH levels at critical junction for exposure zone 4

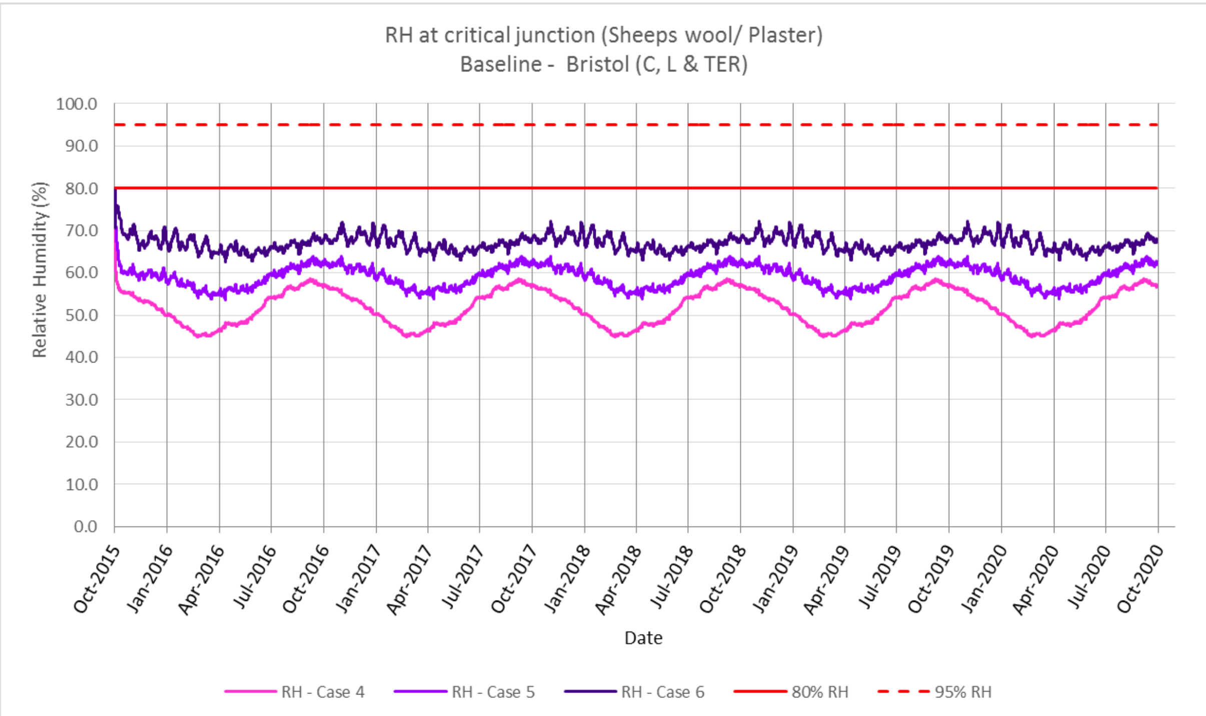


Figure 58: RH levels at critical junction for exposure zone 3

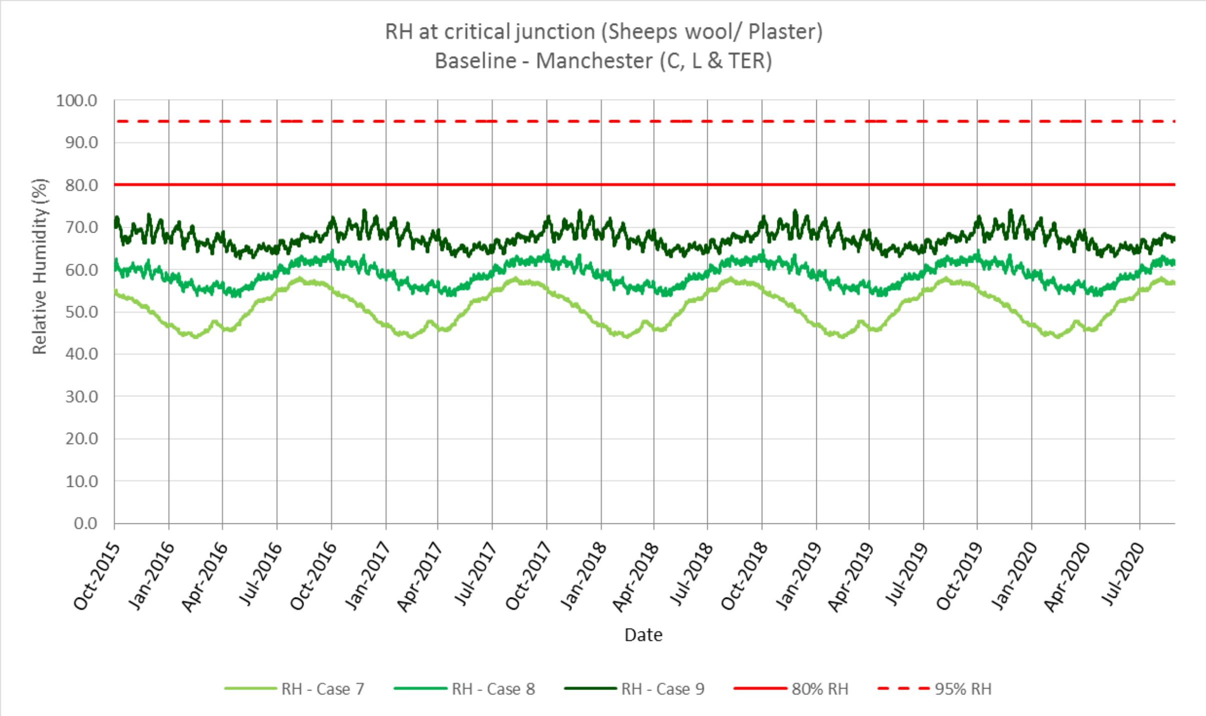


Figure 59: RH levels at critical junction for exposure zone 2

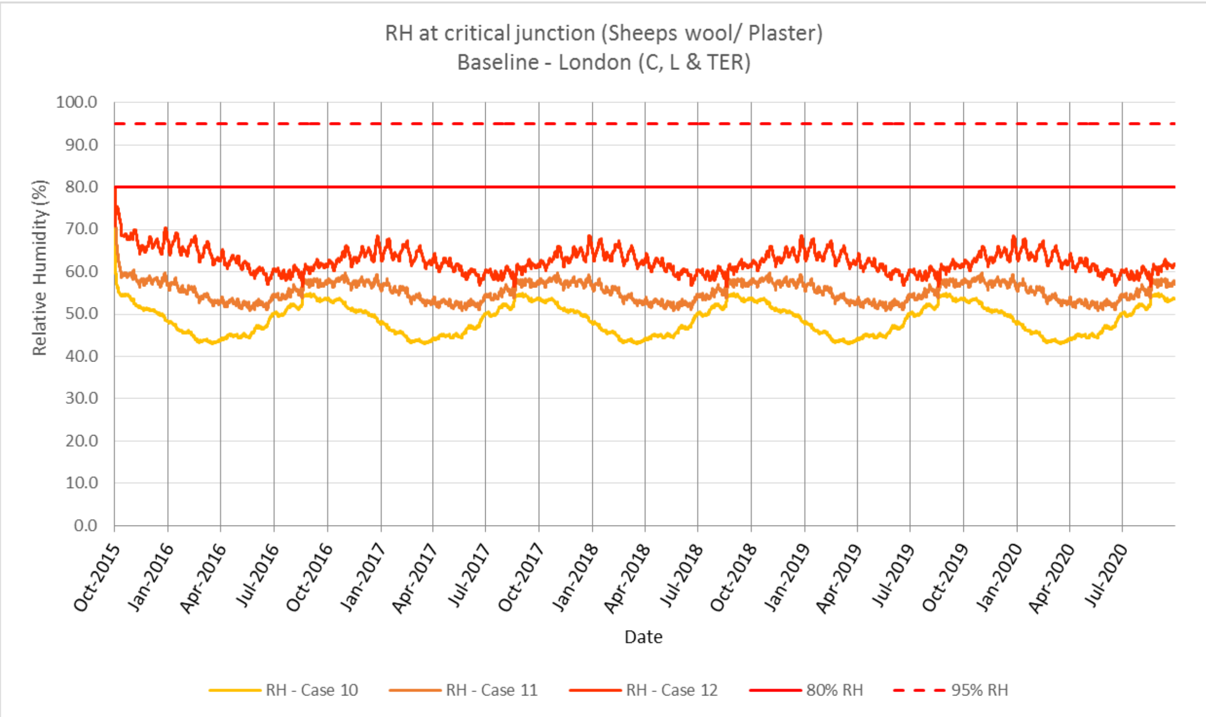


Figure 60: RH levels at critical junction for exposure zone 1

14.3.4. Results Analysis

Moisture risk assessment criteria

All scenarios are 'pass' as they all reach equilibrium, do not accumulate moisture over time and have RH levels well below 80% throughout the modelling period.

In addition, the 80% RH threshold can also be relaxed to 95% for this critical junction, as the build-up meets the four required criteria set out by WTA, 2009 (see section 2.3). For this reason, results showing the results based on the 95% RH threshold are also shown below.

Results

Table 28: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

Table 29: Summary of results with 95% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

Effects of exposure zones

The effect of wind-driven rain exposure zones is visible on the graphs – with lower average RH levels in less exposed zones. This is directly due to different external (and consequently internal) conditions. However, this difference in exposure zones does not alter the status of each case.

Effects of U-value

The most noticeable effect of increasing insulation levels is to shift the peak RH from summer to winter. This tendency is useful since although there are higher peak RH levels for higher levels of insulation , the temperature at this time should be insufficient to encourage mould growth.

14.3.5. Additional Monitored Junction

The critical junction is correctly located in BS 5250 (2011), being the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation.

BS 5250 (2011) also identifies a second interface for cavity walls, which is less at risk but where there might still be a risk for moisture to accumulate, stating: "*Any interstitial condensation which might occur will do so on the inner surface of the external skin, where it is unlikely to cause damage to non-hygroscopic insulation, or insulation which does not fill the cavity.*"

This second interface is not present in the WUFI model, so the monitor closest to the outer surface of the mineral wool cavity wall insulation has been checked.

The results are similar to the same monitored junctions for R11.3 with Wood Fibre IWI and this result is in line with the previous findings from the M7 report, and confirms the previous results. Each case reaches equilibrium, does not accumulate moisture over time, or reach saturation levels of moisture (condensation) with RH levels well below 80% for much or all of the time.

14.4. Conclusions

- Build-up sheltered from the elements and is moisture-open so theoretically safe.
- Exposure zones have small impact.
- As per DECC/ STBA moisture risk assessment. Possibility for 'non-perfect' build-up in practice (ABIS conditions), which could mean possibility that sections of the cavity are bridged allowing more moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair, the risk is negligible, except in conditions of extreme driven rain.

15. Typology R12: Full-fill cavity masonry Retrofit Measure: Internal Wood Fibre Wall Insulation (IWI)

The R12 typology is a cavity wall with full-fill insulation and a semi-porous finish (e.g. facing brickwork) prior to retrofit. The retrofit measure is to add internal wood fibre wall insulation (IWI).

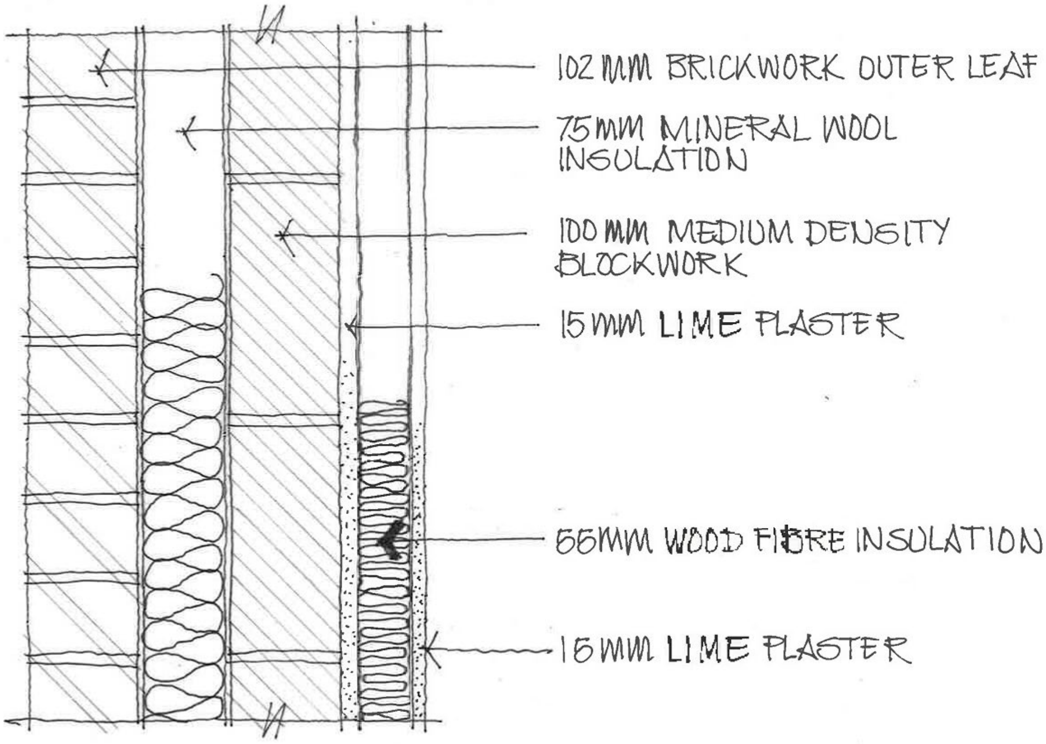


Figure 61: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

15.1. Assessment Method

As the outer brick layer is exposed (and fully part of the build-up, in contrast to the previous R11.1 and R11.3 typologies), the storage of moisture in this layer, as well as the exposure of its external surface to wind-driven rain and solar gains throughout the year, impacts the hygrothermal performance of the build-up. As these elements need to be taken into account but fall outside of the scope of the BS EN ISO 13788 (2012) assessment method, this method cannot be used to provide an accurate assessment.

Due to these limitations, this typology will be assessed with the BS EN 15026 (2007) assessment method using WUFI modelling.

15.2. Build-up

15.2.1. WUFI Build-up (pre-retrofit)

<u>Build-Up:</u>

- 102mm brick outer leaf (hand-formed)
- 75mm mineral wool cavity wall insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

15.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are exposed to wind-driven rain and the brick and block materials are heavy weight materials, with a high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

15.2.3. WUFI Build-up (post-retrofit)

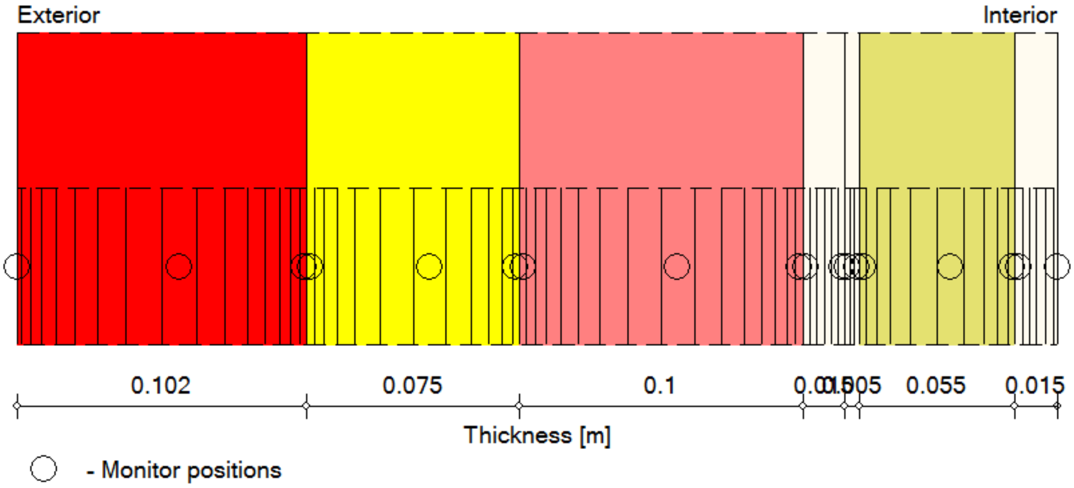
Wood fibre insulation product installation generally requires a 'breathable' substrate on which to attach the insulation layer. Since the original build-up of this wall type has a gypsum plaster finish this is replaced with a new lime plaster along with an additional 5mm 'adhesive' layer with hygrothermal properties similar to that of lime plaster is used both to provide a smooth surface and to help support the wood fibre insulation and lime plaster finish.

In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Since the wall is already insulated beyond the Part C U-value target a nominal 25mm insulation is modelled in lieu of a Part C compliant build-up.

Build-Up:

- 102mm brick outer leaf (hand-formed)
- 75mm mineral wool cavity wall insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm lime plaster (replacing original gypsum plaster)
- 5mm lime plaster (as adhesive)
- 25/55/175 mm Wood fibre insulation (λ = 0.045 W/m.K)
- 15mm lime plaster



Materials:

- Solid Brick, hand-formed	0.102 m
- *Mineral Wool (heat cond.: 0,04 W/mK)	0.075 m
- *Blockwork - medium density	0.1 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.005 m
- *Generic Wood Fibre - unlocked	0.055 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m

Figure 62 - Part L build-up used for WUFI model

Material Physical Properties

While the relevant material properties of the modern construction materials are reasonably consistent and well understood, there is currently a lack of properly tested data for existing UK bricks, stones and plasters.

As this work is generic (no tested data is available), bricks already available in the existing WUFI Pro Fraunhofer database were assumed and selected as being the nearest matches to existing brick walls. These selections were done to obtain a suitable range of data to model brick walls. In the absence of data, it is considered best to opt for conservative assumptions. In this situation, this means that the brick chosen to be used in this modelling is a less ‘performing’ brick in terms of moisture, i.e. a more ‘absorbent’ brick.

Default Brick

The “Solid Brick, hand-formed” from the Fraunhofer IBP database of materials was selected during the setting out of the methodology for this modelling work. This brick is a higher density, less porous brick with a high A-value (0.300 $kg/m^2\sqrt{s}$) – refer to Appendix A. The selection of this brick was based on a paper which tested the A-value of a typical London Brick Fletton brick at 0.32 $kg/m^2\sqrt{s}$ (Rirsch & Zhang, 2012). This is one of the few known moisture tests of a UK brick with publicly available results.

In the absence of what is considered a ‘typical’ brick in the industry, including its full physical properties, the decision was taken to use this brick as the default brick in this modelling work. This is also one of the most absorbent bricks in the Fraunhofer WUFI database and therefore gives a good representation of “worst case scenario” in terms of brick characteristics.

15.3. Baseline Results

15.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the equilibrium (pre-retrofit) cases and the cases meeting the Part L target U-value, as set out below.

Table 30: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

15.3.2. Critical / Monitored Junction

BS 5250 (2011) paragraph G.4.2.4 states that: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*. Therefore the location of concern at the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation.

15.3.3. Graphs at Critical Junction

The graphs displayed below show the RH levels for each location at the critical junction:

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

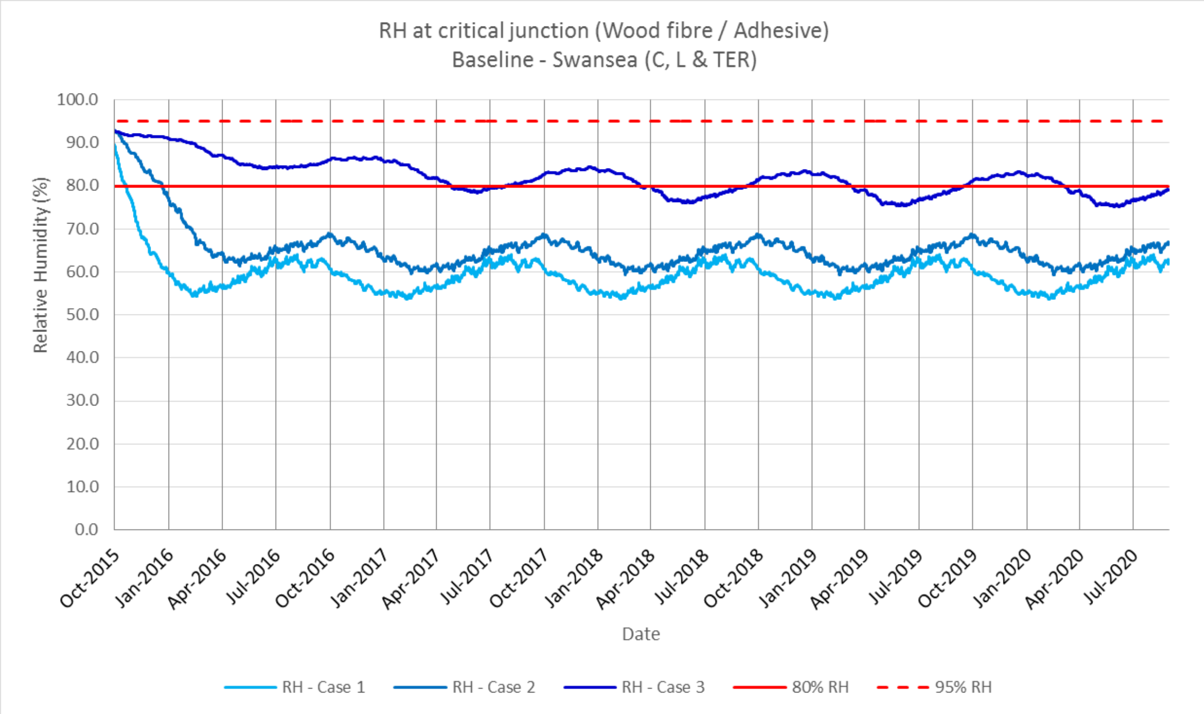


Figure 63: RH levels at critical junction for exposure zone 4

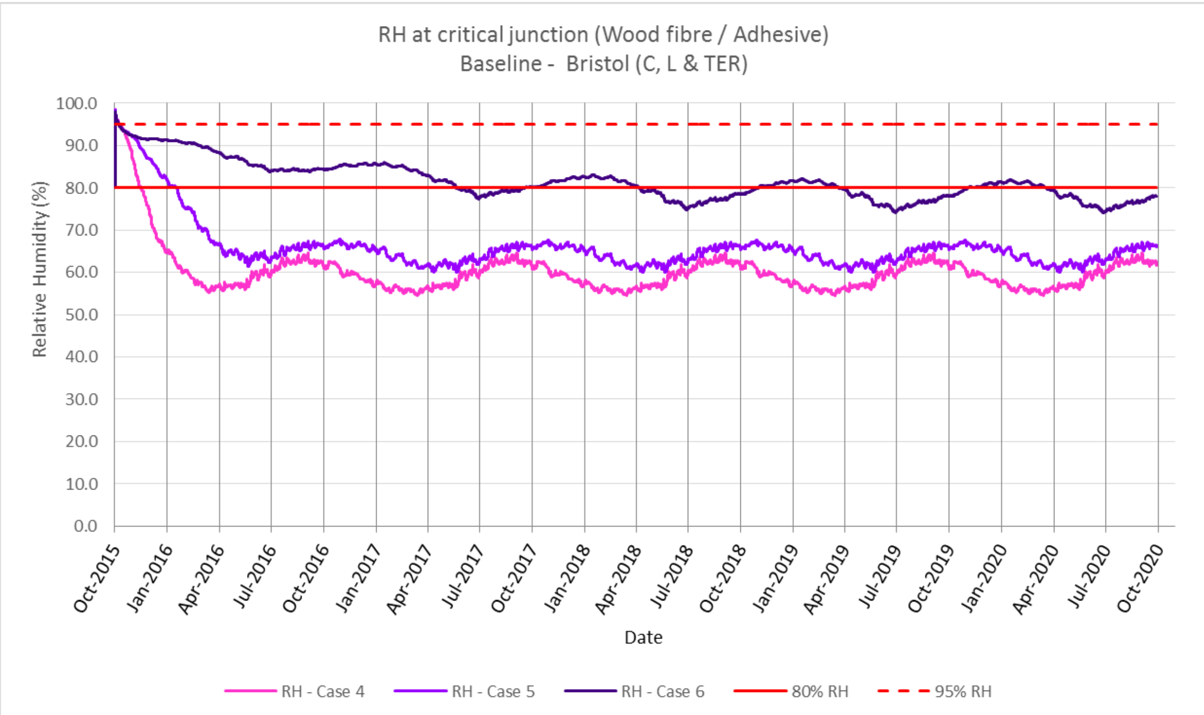


Figure 64: RH levels at critical junction for exposure zone 3

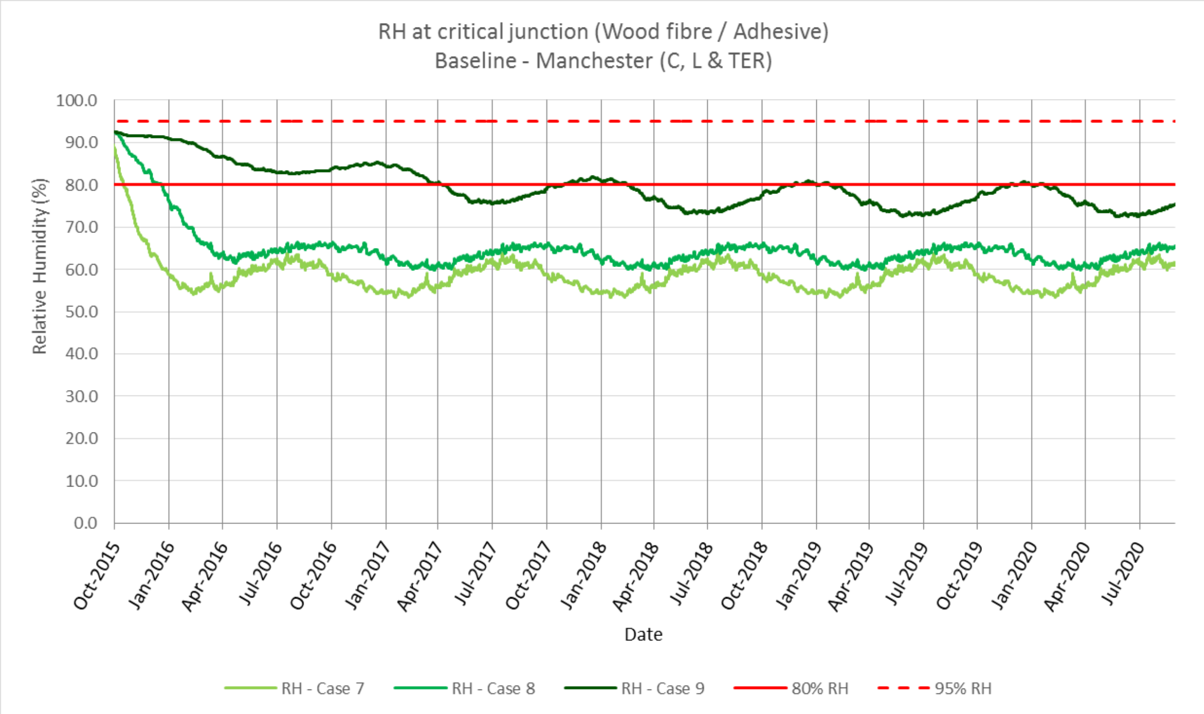


Figure 65: RH levels at critical junction for exposure zone 2

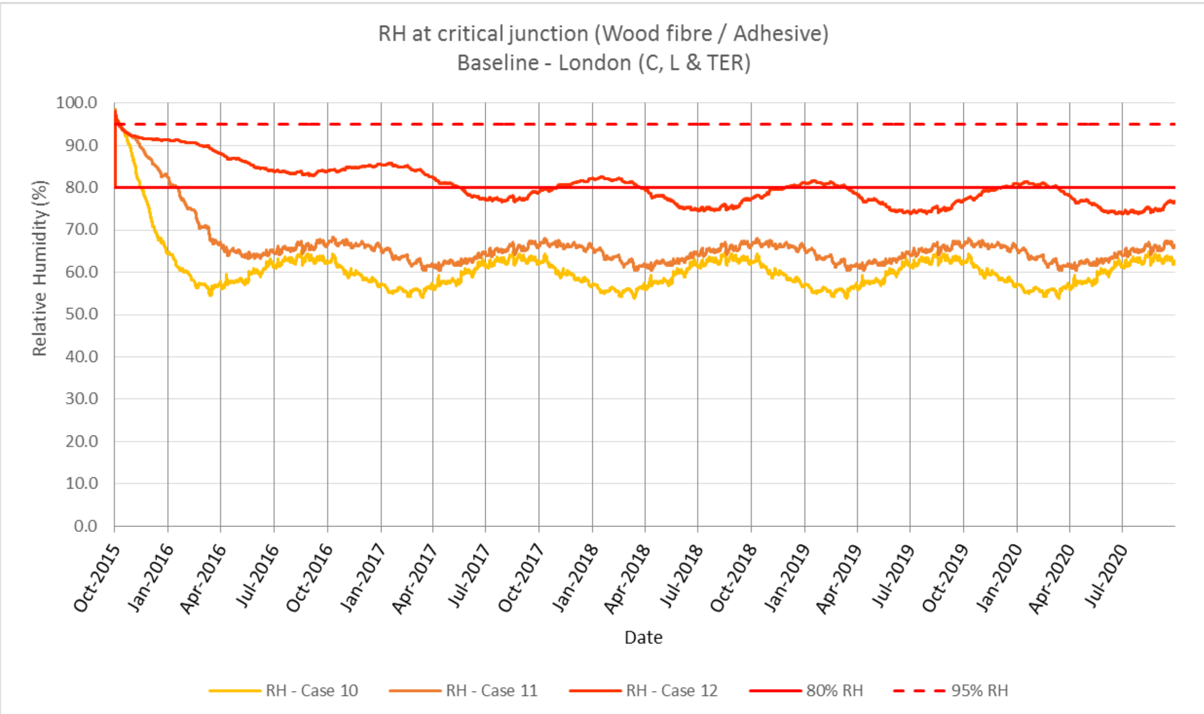


Figure 66: RH levels at critical junction for exposure zone 1

15.3.4. Results Analysis

Moisture risk assessment criteria

The 80% RH threshold can be considered for relaxation to 95% for this critical junction. Although the build-up does not strictly meet the four required criteria set out by WTA, 2009 (see section 2.3), insofar as the second criteria "use of renders, rain-screens or impregnations that prevent driving rain ingress" is not met, since the outer brickwork is exposed. However, the effect of wind driven rain are physically removed from the structural build-up by the presence of the mineral wool cavity insulation. For this reason, results showing the results based on the 95% RH threshold are also shown below.

Results

Table 31: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	Swansea (Zone 4)	Bristol (Zone 3)	Manchester (Zone 2)	London (Zone 1)
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Fail	Fail	Fail	Fail

Table 32: Summary of results with 95% RH threshold

	Exposure Zones			
Target U-values	Swansea (Zone 4)	Bristol (Zone 3)	Manchester (Zone 2)	London (Zone 1)
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

All scenarios reach equilibrium, and do not accumulate moisture over time. However, as scenarios with high levels of insulation (TER case) spending periods of time at or above the 80% RH threshold.

In addition, all scenarios spend lengthy periods of time initially above the 80% RH threshold at the beginning of the modelling period. This is likely to be due to the high initial moisture levels in the lime plaster and adhesive layers.

Effects of exposure zones

Although the difference in exposure zones is visually noticeable on the graphs, as they show that build-ups in zones that are more exposed to wind-driven rain display on average higher RH levels at critical junctions, as well as a more prolonged period, this effect is not pronounced since the inner leaf is physically removed from and also protected from external weather by the cavity mineral wool insulation.

Effects of U-value

The most noticeable effect of increasing insulation levels is to shift the peak RH from summer to winter. This tendency is useful since although there are higher peak RH levels for higher levels of insulation , the temperature at this time should be insufficient to encourage mould growth.

As expected with internal wall insulation; the higher the level of insulation, the higher the moisture levels at the critical junction. The levels of insulation required in order to achieve the lower U-value targets is unlikely to be installed in practice since the insulation would be 'too thick' to be practical.

Effects of Brick Physical Properties

The main moisture source creating problems in an exposed wall build-up is rain penetration from the outside. As the external wall, in this build-up, is not protected, moisture (as liquid water) penetrates deeper into the build-up in the winter via capillary action due to wind-driven rain reaching the façade. As both cavity wall and internal wall insulation is installed directly in contact with the wall structure, the cold side of both insulation layers are exposed to the conditions experienced by the inner surface of the brickwork and blockwork respectively.

However, it is worth noting that this baseline modelling is done using the worst case scenario regarding the physical characteristics of the brick material, which means that the build-up’s hygrothermal performance might be improved when ‘better-performing’ bricks (in terms of moisture properties) are used.

15.3.5. Additional Monitored Junction

The critical junction is correctly located in BS 5250 (2011), being the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation.

BS 5250 (2011) also identifies a second interface for cavity walls, which is less at risk but where there might still be a risk for moisture to accumulate, stating: "*Any interstitial condensation which might occur will do so on the inner surface of the external skin, where it is unlikely to cause damage to non-hygroscopic insulation, or insulation which does not fill the cavity.*"

The chart show both the exposure zone 4 TER case and the exposure zone 1 part C case to illustrate the extreme cases within the modelling regime.

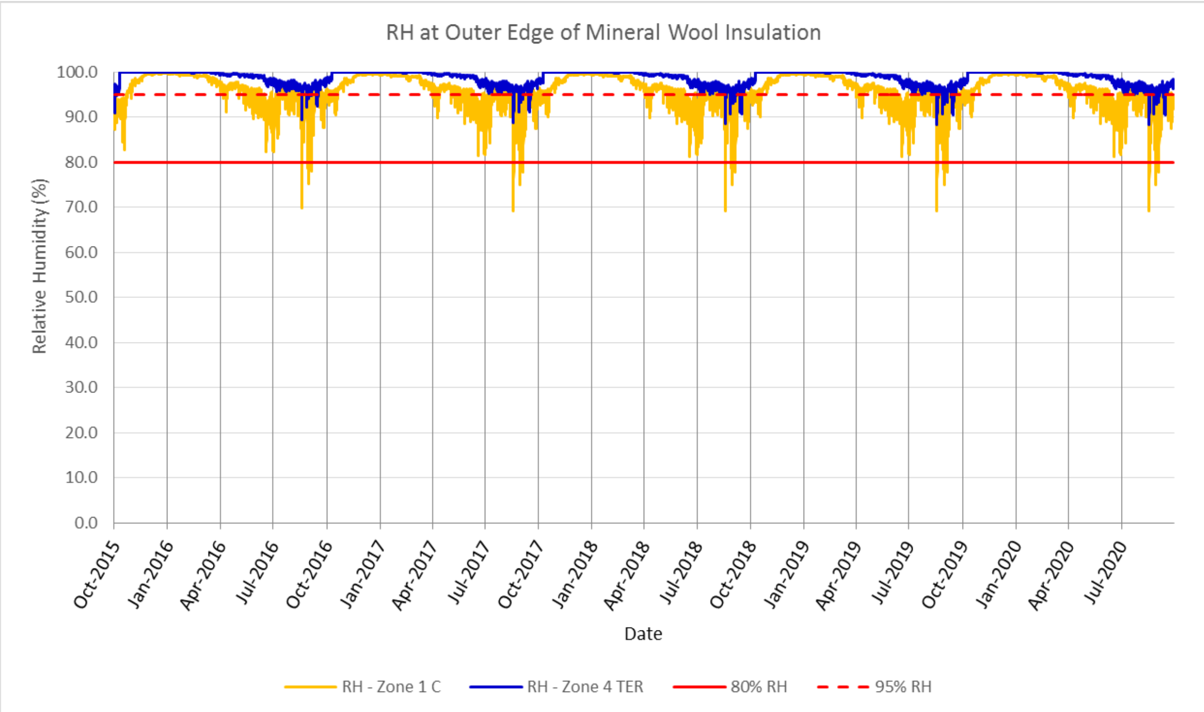


Figure 67: RH levels at additional monitored junction

This result is in line with the previous findings from the M7 report, and confirms the previous results as all cases reach equilibrium very quickly. However, all of the cases monitored at the interface between the outer brick leaf and the cavity wall insulation display RH levels well above 95% and reaching 100% (i.e. interstitial condensation) up to several months a year.

In addition, RH levels are still above 80% throughout the year (including the summer season, when temperatures are high enough to promote mould growth). The subject of buildability with cavity walls has also been raised with the R12 typology (full-fill cavity wall). It is possible for a small air gap to be present in between the outer brickwork layer and the insulation for diverse buildability reasons (insulation being squashed and not expanding through the whole cavity, insulation not being thick enough, etc.). It is also likely for mould growth to find a food source (even if not abundant), which means all the conditions for mould growth could be met at this interface.

As mentioned before, the risk was highlighted in paragraph G.4.2.3 in BS 5250 (2011) but the guidance also mentions that it should not lead to any damages provided these risks are well taken into account and dealt with (with the use of non-hygroscopic materials and provision to allow for any accumulated moisture to be drained out of the cavity).

Therefore, if mould growth were to occur, as its location is isolated from the indoor environment, there would be no significant consequences to the build-up or the health of building occupants.

15.3.6. Conclusions – Baseline

- Build-up hygrothermal performance is linked to exposure zone: the more exposed the build-up is, the higher the RH levels experienced although all cases show up to 100% RH leading to interstitial condensation on the inner surface of the outer brickwork.
- Presence of interstitial condensation, though not a significant issue as interstitial condensation accounted for and interstitial condensation removal process included in build-up.
- Question about thermal conductivity (+ thermal performance) of insulation when constantly submitted to high RH levels (> 80%)
- Risk of mould growth behind internal wall insulation probably worsened for 'non-perfect' build-up in practice (ABIS conditions), which could mean the presence of food and air for mould growth and direct contact with the internal environment, so not recommended on the inner surface of the insulation).

<u>STBA / DECC's guidance</u>
'There is the possibility that the insulation will bridge the cavity allowing moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair and the insulation has been properly installed, the risk is negligible, except in conditions of extreme driven rain'

(This is an extract from the STBA / DECC's guidance, which is the latest guidance on this build-up. It is suggesting that this build-up is safe except in extreme driven rain (i.e. Zone 4) and therefore conclusion to include and compare our findings with this guidance.

Prolonged rain has been predicted as part of the climate change. Since more rainfall is likely to mean more wind-driven rain, it may have a greater impact.

16. Typology R12: Full-fill cavity masonry Retrofit Measure: Internal Calcium Silicate Board Wall Insulation (IWI)

The R12 typology is a cavity wall with full-fill insulation and a semi-porous finish (e.g. facing brickwork) prior to retrofit. The retrofit measure is to add internal Calcium Silicate Board wall insulation (IWI).

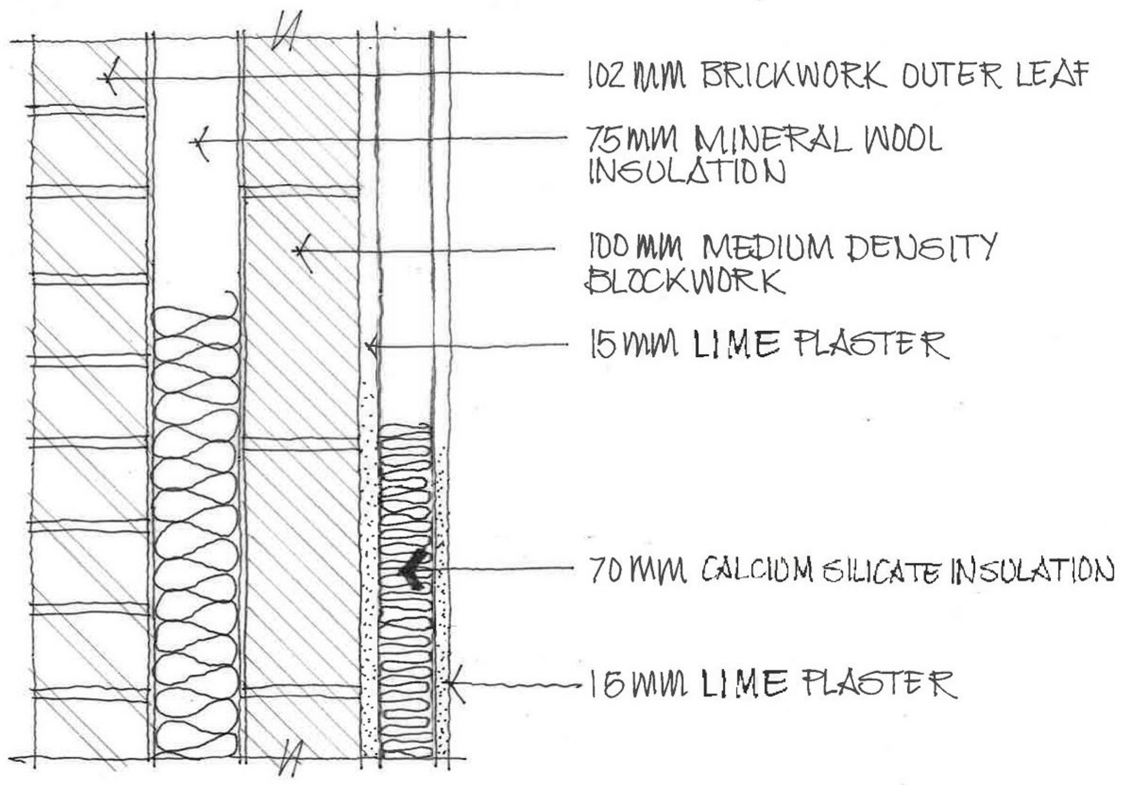


Figure 68: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

16.1. Assessment Method

As the outer brick layer is exposed (and fully part of the build-up, contrary to the previous R11.1 and R11.3 typologies), the storage of moisture in this layer, as well as the exposure of its external surface to wind-driven rain and solar gains throughout the year, impacts the hygrothermal performance of the build-up. As these elements need to be taken into account but fall outside of the scope of the BS EN ISO 13788 (2012) assessment method, this method cannot be used to provide an accurate assessment.

Due to these limitations, this typology will be assessed with the BS EN 15026 (2007) assessment method using WUFI modelling.

16.2. Build-up

16.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 102mm brick outer leaf (hand-formed)
- 75mm mineral wool cavity wall insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

16.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are exposed to wind-driven rain and the brick and block materials are heavy weight materials, with a high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

16.2.3. WUFI Build-up (post-retrofit)

Substrate
Calcium Silicate board product installation generally requires a 'breathable' substrate on which to attach the insulation layer. Since the original build-up of this wall type has a gypsum plaster finish – which is not considered to be an adequate substrate for the calcium silicate insulation boards, this is replaced with a new lime plaster along with an additional 5mm adhesive layer (cementitious dry mortar).

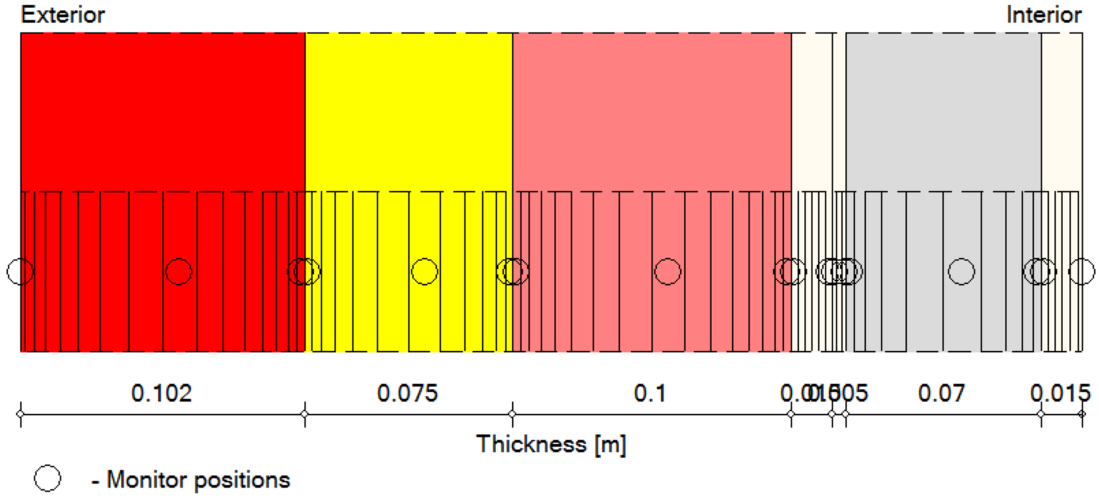
The WUFI material “SAKRET Klebe- und Armierungsmörtel leicht KAM-L” is considered the closest WUFI material to represent the cementitious dry mortar adhesive material, to fix the calcium silicate insulation boards.

In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Since the wall is already insulated beyond the Part C U-value target, a nominal 25mm insulation is modelled in lieu of a Part C compliant build-up.

Build-Up:

- 102mm brick outer leaf (hand-formed)
- 75mm mineral wool cavity wall insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm lime plaster (replacing original gypsum plaster)
- 5mm Adhesive layer (cementitious dry mortar)
- 25/70/215 mm Calcium silicate board insulation (λ = 0.055 W/m.K)
- 15mm lime plaster



Materials:

- Solid Brick, hand-formed	0.102 m
- *Mineral Wool (heat cond.: 0,04 W/mK)	0.075 m
- *Blockwork - medium density	0.1 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.005 m
- *Calcium Silikates - unlocked	0.07 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m

Figure 69 - Part L build-up used for WUFI model

Material Physical Properties

While the relevant material properties of the modern construction materials are reasonably consistent and well understood, there is currently a lack of properly tested data for existing UK bricks, stones and plasters.

As this work is generic (no tested data is available), bricks already available in the existing WUFI Pro Fraunhofer database were assumed and selected as being the nearest matches to existing brick walls. These selections were done to obtain a suitable range of data to model brick walls. In the absence of data, it is considered best to opt for conservative assumptions. In this situation, this means that the brick chosen to be used in this modelling is a less 'performing' brick in terms of moisture, i.e. a more 'absorbent' brick.

Default Brick

The "Solid Brick, hand-formed" from the Fraunhofer IBP database of materials was selected during the setting out of the methodology for this modelling work. This brick is a higher density, less porous brick with a high A-value (0.300 $kg/m^2\sqrt{s}$) – refer to Appendix A. The selection of this brick was based on a paper which tested the A-value of a typical London Brick Fletton brick at 0.32 $kg/m^2\sqrt{s}$ (Rirsch & Zhang, 2012). This is one of the few known moisture tests of a UK brick with publicly available results.

In the absence of what is considered a 'typical' brick in the industry, including its full physical properties, the decision was taken to use this brick as the default brick in this modelling work. This is also one of the most absorbent bricks in the Fraunhofer WUFI database and therefore should give a good representation of "worst case scenario" in terms of brick characteristics.

16.3. Baseline Results

16.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the cases meeting the Part C, Part L and TER target U-values, as set out below.

Table 33: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

16.3.2. Critical / Monitored Junction

BS 5250 (2011) paragraph G.4.2.4 states that: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*. Therefore the location of concern at the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation.

16.3.3. Graphs at Critical Junctions

The graphs displayed below show the RH levels for each location at the critical junction:

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

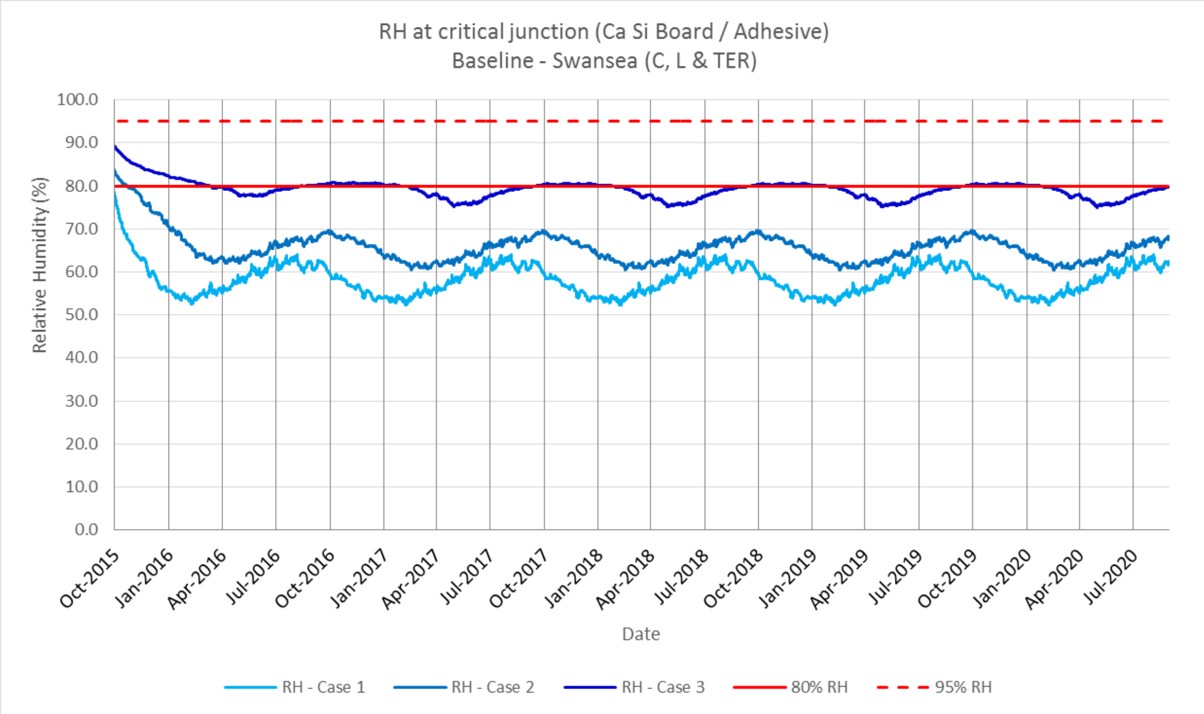


Figure 70: RH levels at critical junction for exposure zone 4

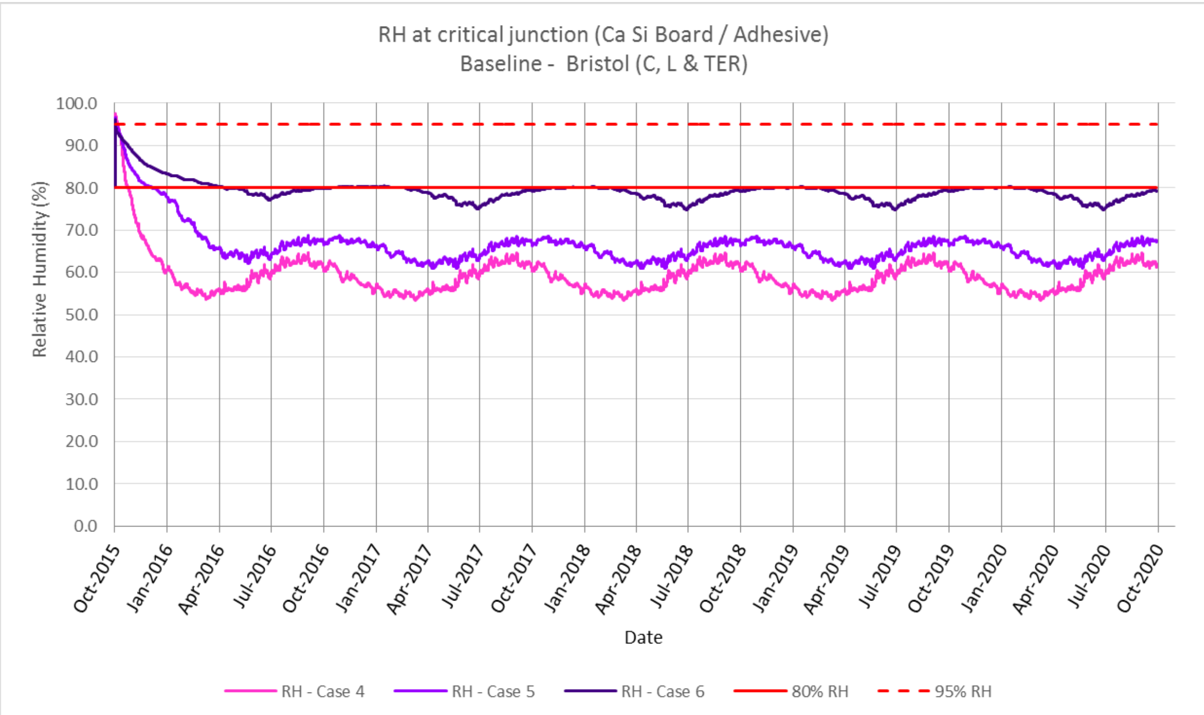


Figure 71: RH levels at critical junction for exposure zone 3

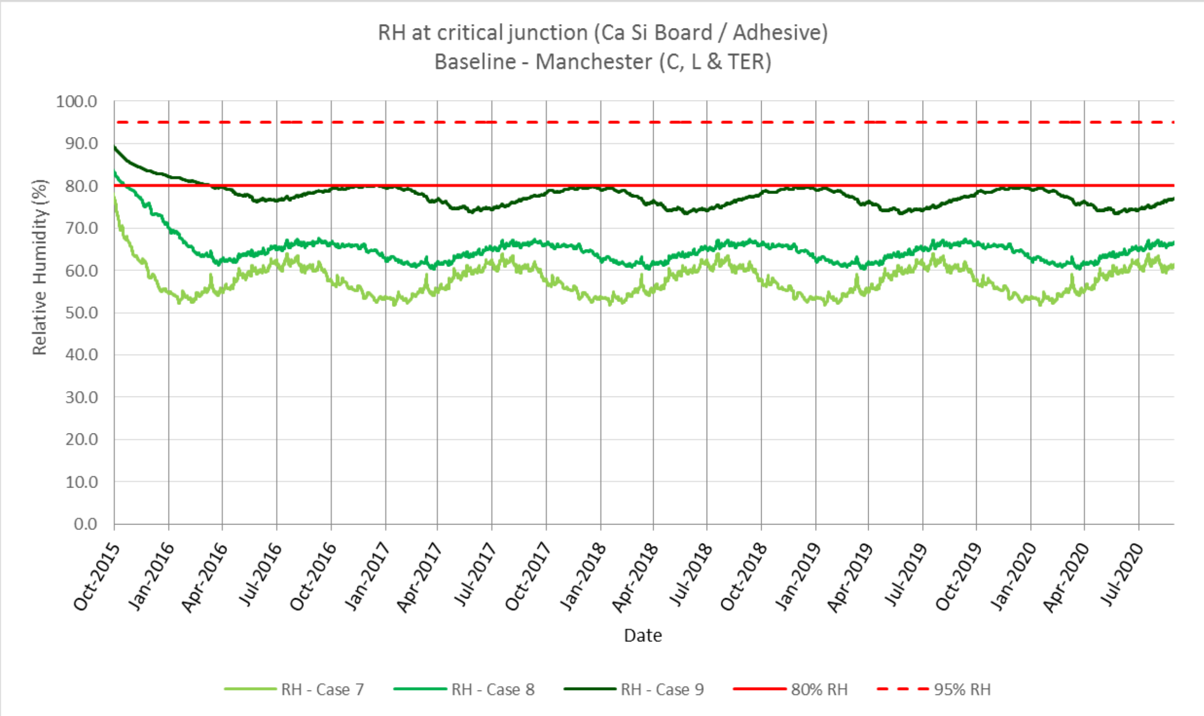


Figure 72: RH levels at critical junction for exposure zone 2

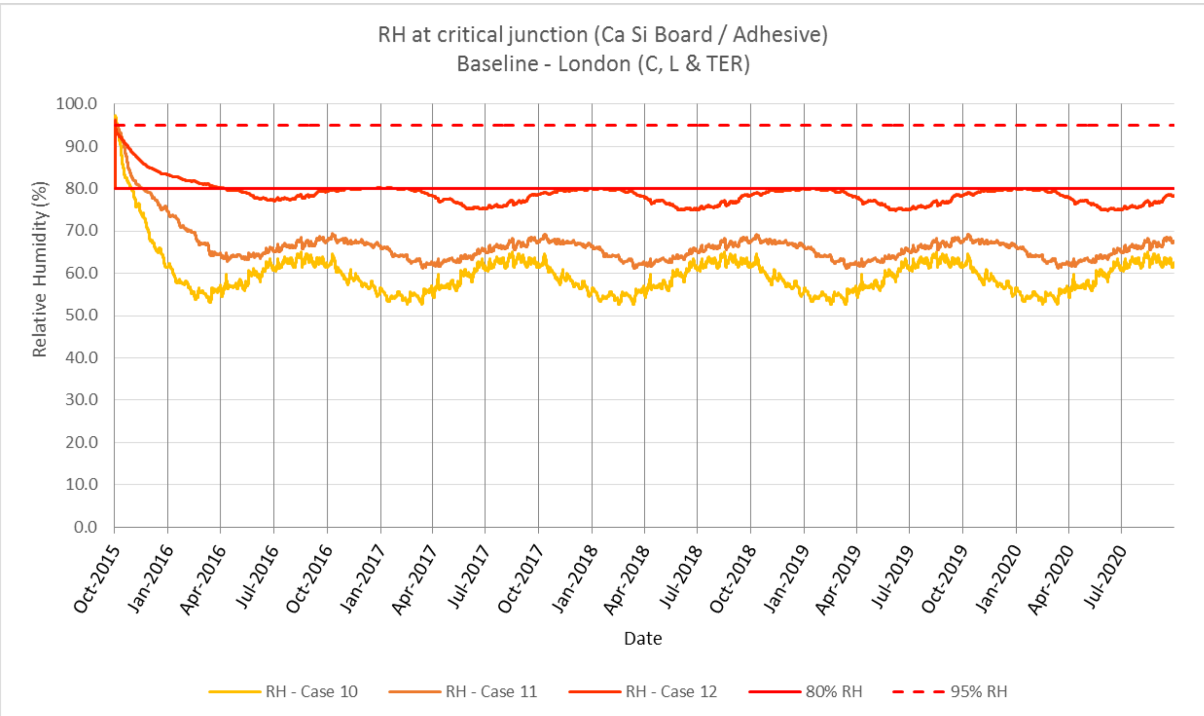


Figure 73: RH levels at critical junction for exposure zone 1

16.3.4. Results Analysis

Moisture risk assessment criteria

The 80% RH threshold can be considered for relaxation to 95% for this critical junction. Although the build-up does not strictly meet the four required criteria set out by WTA, 2009 (see section 2.3), insofar as the second criteria "use of renders, rain-screens or impregnations that prevent driving rain ingress" is not met, since the outer brickwork is exposed. However, the effect of wind driven rain are physically removed from the structural build-up by the presence of the mineral wool cavity insulation. For this reason, results showing the results based on the 95% RH threshold are also shown below.

Exposure Zone 4 with the highest level of insulation has RH levels over 80% for periods greater than one month and so can be considered to 'fail' this criteria.

All other exposure zones with the highest levels of insulation have RH levels at 80 for periods greater than one month and so can be considered to be 'risky'.

All exposure zones with the levels of insulation to reach the Part C or Part L requirement have RH levels below 80% continuously after equilibrium is reached with RH levels above 80% due to initial conditions only for up to 3 months.

Results

Table 34: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Fail	Risky	Risky	Risky

Table 35: Summary of results with 95% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

Effects of exposure zones

The difference in exposure zones is small but noticeable on the graphs, with build-ups in zones that are more exposed to wind-driven rain displaying on average higher RH levels at critical junctions. This finding is as predicted, since the hygrothermal performance of exposed brick walls is directly affected by the external conditions.

However wind-driven rain exposure zones are not “driving” the status of the cases – as U-values / insulation thicknesses have a much bigger impact of the hygrothermal performance of the build-ups.

Effects of U-value

The most noticeable effect of increasing insulation levels is to shift the peak RH from summer to winter. This tendency is useful since although there are higher peak RH levels for higher levels of insulation , the temperature at this time should be insufficient to encourage mould growth.

As expected with internal wall insulation; the higher the level of insulation, the higher the moisture levels at the critical junction. The levels of insulation required in order to achieve the lower U-value targets is unlikely to be installed in practice since the insulation would be 'too thick' to be practical.

Effects of Brick Physical Properties

The main moisture source creating problems in an exposed wall build-up is rain penetration from the outside. As the external wall, in this build-up, is not protected, moisture (as liquid water) penetrates deeper into the build-up in the winter via capillary action due to wind-driven rain reaching the façade. As both cavity wall and internal wall insulation is installed directly in contact with the wall structure, the cold side of both insulation layers are exposed to the conditions experienced by the inner surface of the brickwork and blockwork respectively.

However, it is worth noting that this baseline modelling is done using the worst case scenario regarding the physical characteristics of the brick material, which means that the build-up’s hygrothermal performance might be improved when ‘better-performing’ bricks (in terms of moisture properties) are used.

16.3.5. Additional Monitored Junction

The critical junction is correctly located in BS 5250 (2011), being the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation.

BS 5250 (2011) also identifies a second interface for cavity walls, which is less at risk but where there might still be a risk for moisture to accumulate, stating: "*Any interstitial condensation which might occur will do so on the inner surface of the external skin, where it is unlikely to cause damage to non-hygroscopic insulation, or insulation which does not fill the cavity.*"

The results are similar to the same monitored junctions for R12 with Wood Fibre IWI and this result is in line with the previous findings from the M7 report, and confirms the previous results as all cases reach equilibrium very quickly. However, all of the cases monitored at the interface between the outer brick leaf and the cavity wall insulation display RH levels well above 95% and reaching 100% (i.e. interstitial condensation) up to several months a year.

In addition, RH levels are still above 80% throughout the year (including the summer season, when temperatures are high enough to promote mould growth). The subject of buildability with cavity walls has also been raised with the R12 typology (full-fill cavity wall). It is possible for a small air gap to be present in between the outer brickwork layer and the insulation for diverse buildability reasons (insulation being squashed and not expanding through the whole cavity, insulation not being thick enough, etc.). It is also likely for mould growth to find a food source (even if not abundant), which means all the conditions for mould growth could be met at this interface.

As mentioned before, the risk was highlighted in paragraph G.4.2.3 in BS 5250 (2011) but the guidance also mentions that it should not lead to any damages provided these risks are well taken into account and dealt with (with the use of non-hygroscopic materials and provision to allow for any accumulated moisture to be drained out of the cavity).

Therefore, if mould growth were to occur, as its location is isolated from the indoor environment, there would be no significant consequences to the build-up or the health of building occupants.

16.3.6. Conclusions – Baseline

- Build-up hygrothermal performance is linked to exposure zone: the more exposed the build-up is, the higher the RH levels experienced although all cases show up to 100% RH leading to interstitial condensation on the inner surface of the outer brickwork
- Presence of interstitial condensation, though not a significant issue as interstitial condensation accounted for and interstitial condensation removal process included in build-up
- Question about thermal conductivity (+ thermal performance) of insulation when constantly submitted to high RH levels (> 80%)
- Risk of mould growth behind internal wall insulation probably worsened for ‘non-perfect’ build-up in practice (ABIS conditions), which could mean the presence of food and air for mould growth and direct contact with the internal environment, so not recommended on the inner surface of the insulation).

<u>STBA / DECC's guidance</u>
‘There is the possibility that the insulation will bridge the cavity allowing moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair and the insulation has been properly installed, the risk is negligible, except in conditions of extreme driven rain‘

(This is an extract from the STBA / DECC's guidance, which is the latest guidance on this build-up. It is suggesting that this build-up is safe except in extreme driven rain (i.e. Zone 4) and therefore conclusion to include and compare our findings with this guidance.

Prolonged rain has been predicted as part of the climate change. Since more rainfall is likely to mean more wind-driven rain, it may have a greater impact. To be included as a future consideration.

17. Typology R12: Full-fill cavity masonry Retrofit Measure: Internal Sheep's Wool Wall Insulation (IWI)

The R12 typology is a cavity wall with full-fill insulation and a semi-porous finish (e.g. facing brickwork) prior to retrofit. The retrofit measure is to add internal Sheep's Wool wall insulation (IWI).

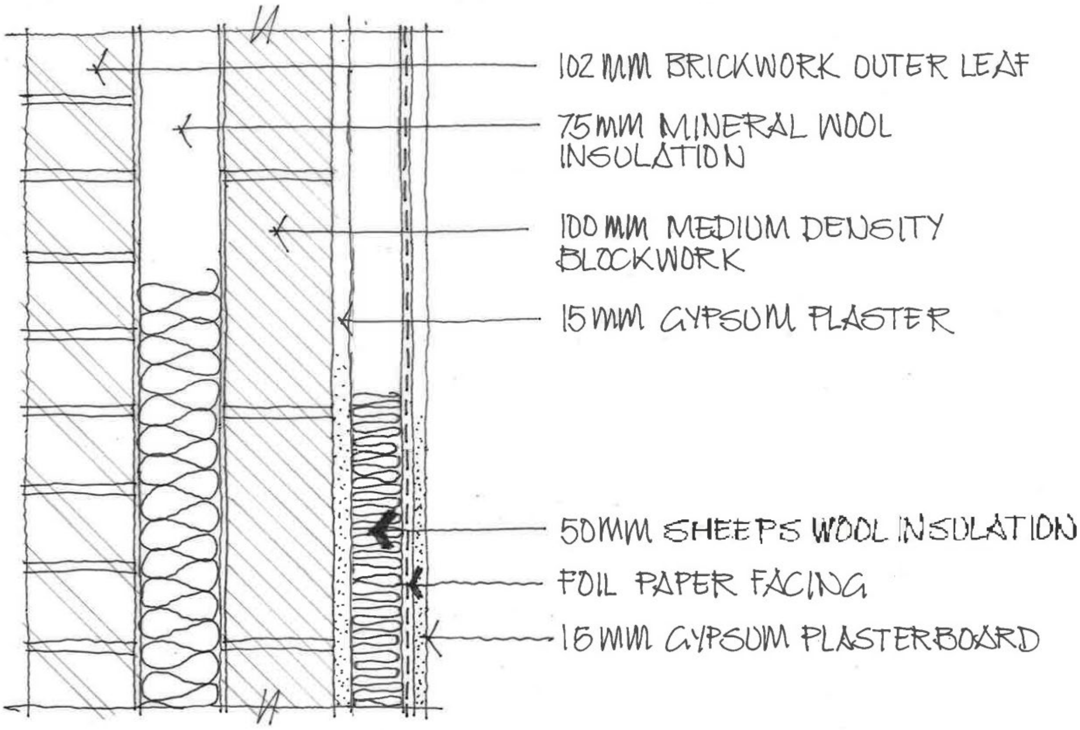


Figure 74: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

17.1. Assessment Method

As the outer brick layer is exposed (and fully part of the build-up, contrary to the previous R11.1 and R11.3 typologies), the storage of moisture in this layer, as well as the exposure of its external surface to wind-driven rain and solar gains throughout the year, impacts the hygrothermal performance of the build-up. As these elements need to be taken into account but fall outside of the scope of the BS EN ISO 13788 (2012) assessment method, this method cannot be used to provide an accurate assessment.

Due to these limitations, this typology will be assessed with the BS EN 15026 (2007) assessment method using WUFI modelling.

17.2. Build-up

17.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 102mm brick outer leaf (hand-formed)
- 75mm mineral wool cavity wall insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

17.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are exposed to wind-driven rain and the brick and block materials are heavy weight materials, with a high moisture storage capacity. Therefore, it is necessary to run the pre-retrofit model to establish equilibrium levels and use the resultant equilibrium values as initial values for existing layers in the baseline cases.

17.2.3. WUFI Build-up (post-retrofit)

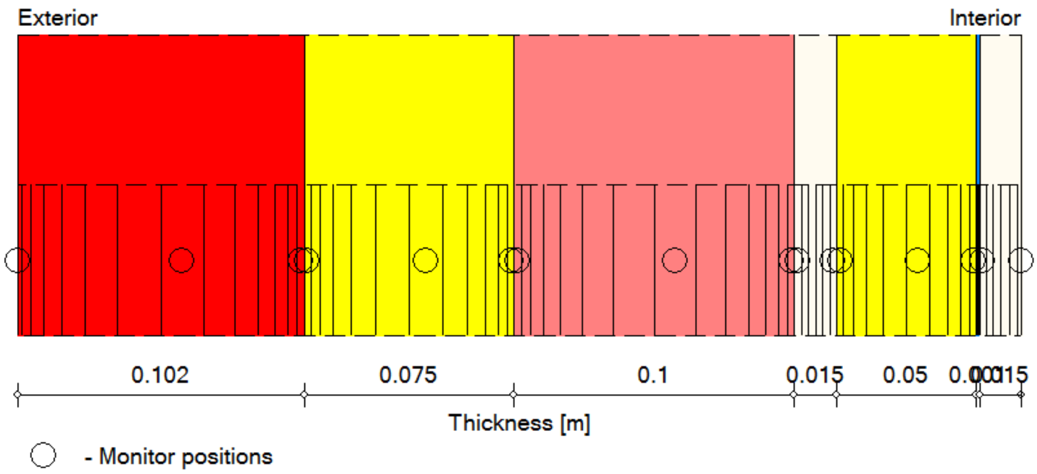
Substrate
Sheep's wool insulation product installation guidance generally do not requires any particular substrate on which to attach the insulation layer. The original gypsum plaster finish is therefore retained. Sheep's wool insulation is typically installed between battens and finished with a foil backed plasterboard.

In practice, it is unlikely for any retrofitted internal wall insulation layer to exceed 100mm including finishes. Due to the research nature of this piece of work, we have calculated required retrofitted insulation layer thicknesses to match target U-values. However, in the case of TER target U-values, this sometimes results in unrealistic / excessively large insulation thicknesses, but the modelling was carried out despite these practical issues, to understand the impact of insulation thicknesses on the chosen build-ups.

Since the wall is already insulated beyond the Part C U-value target, a nominal 25mm insulation is modelled in lieu of a Part C compliant build-up.

Build-Up:

- 102mm brick outer leaf (hand-formed)
- 75mm mineral wool cavity wall insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster
- 25/50/160mm Sheep’s wool insulation (λ = 0.036 W/m.K) installed between timber battens
- 1mm foil paper facing (sd = 14m)
- 15mm gypsum plasterboard



Materials:

- Solid Brick, hand-formed	0.102 m
- *Mineral Wool (heat cond.: 0,04 W/mK)	0.075 m
- *Blockwork - medium density	0.1 m
- Interior Plaster (Gypsum Plaster)	0.015 m
- *Sheeps wool	0.05 m
- *Foil paper facing (sd = 14m) (unlocked)	0.001 m
- Gypsum Board	0.015 m

Figure 75 - Part L build-up used for WUFI model

Material Physical Properties

While the relevant material properties of the modern construction materials are reasonably consistent and well understood, there is currently a lack of properly tested data for existing UK bricks, stones and plasters.

As this work is generic (no tested data is available), bricks already available in the existing WUFI Pro Fraunhofer database were assumed and selected as being the nearest matches to existing brick walls. These selections were done to obtain a suitable range of data to model brick walls. In the absence of data, it is considered best to opt for conservative assumptions. In this situation, this means that the brick chosen to be used in this modelling is a less 'performing' brick in terms of moisture, i.e. a more 'absorbent' brick.

Default Brick

The "Solid Brick, hand-formed" from the Fraunhofer IBP database of materials was selected during the setting out of the methodology for this modelling work. This brick is a higher density, less porous brick with a high A-value (0.300 $kg/m^2\sqrt{s}$) – refer to Appendix A. The selection of this brick was based on a paper which tested the A-value of a typical London Brick Fletton brick at 0.32 $kg/m^2\sqrt{s}$ (Rirsch & Zhang, 2012). This is one of the few known moisture tests of a UK brick with publicly available results.

In the absence of what is considered a 'typical' brick in the industry, including its full physical properties, the decision was taken to use this brick as the default brick in this modelling work. This is also one of the most absorbent bricks in the Fraunhofer WUFI database and therefore gives a good representation of "worst case scenario" in terms of brick characteristics.

17.3. Baseline Results

17.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, for the cases meeting the Part C, Part L and TER target U-values, as set out below.

Table 36: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C (0.7)	Case 1	Case 4	Case 7	Case 10
Part L (0.3)	Case 2	Case 5	Case 8	Case 11
TER (0.18)	Case 3	Case 6	Case 9	Case 12

17.3.2. Critical / Monitored Junction

BS 5250 (2011) paragraph G.4.2.4 states that: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation'*. Therefore the location of concern at the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation.

17.3.3. Graphs at Critical Junctions

The graphs displayed below show the RH levels for each location at the critical junction:

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1).

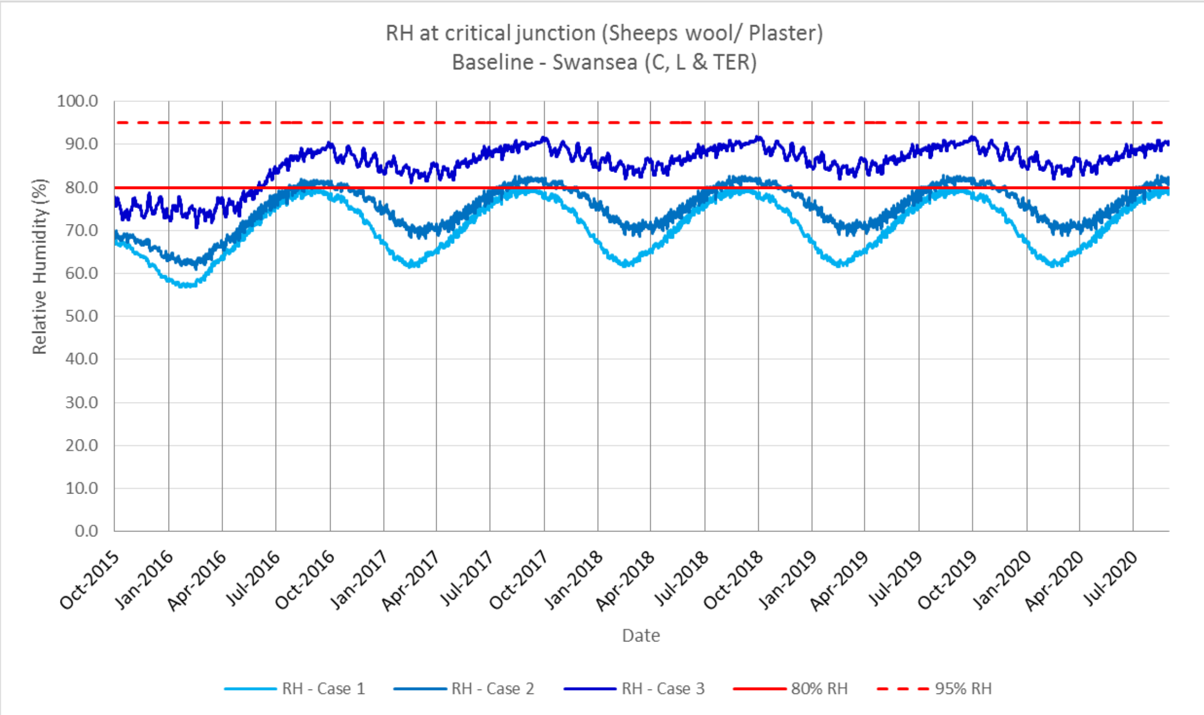


Figure 76: RH levels at critical junction for exposure zone 4

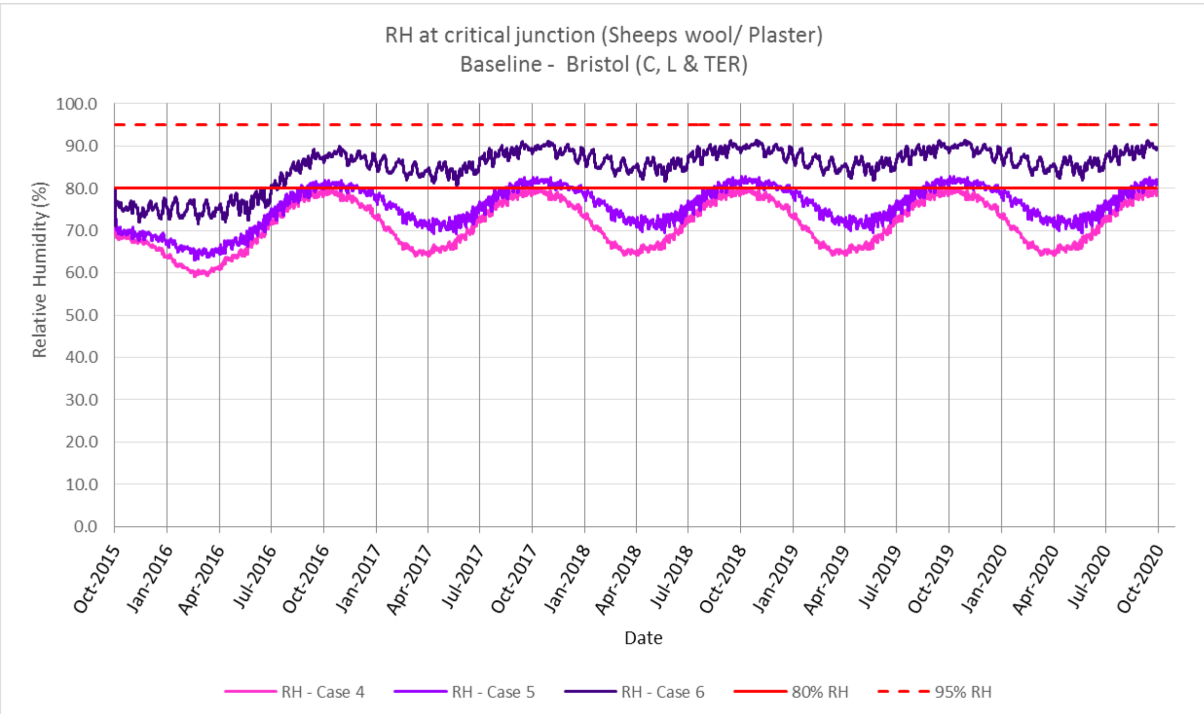


Figure 77: RH levels at critical junction for exposure zone 3

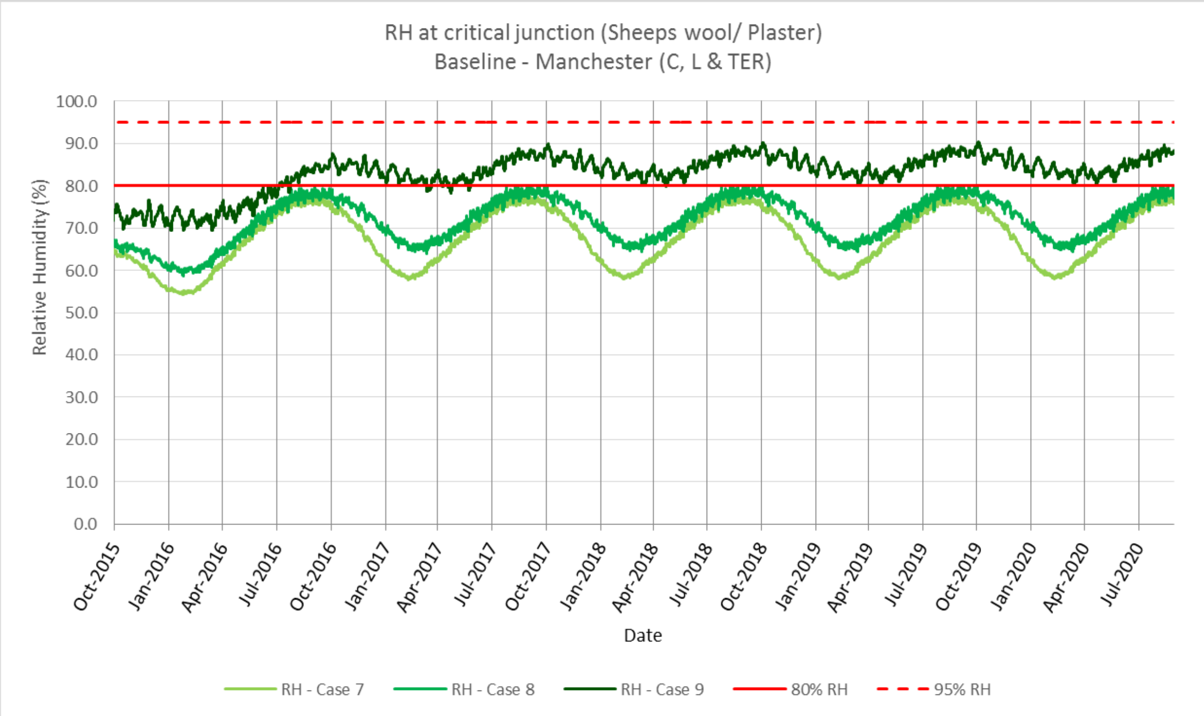


Figure 78: RH levels at critical junction for exposure zone 2

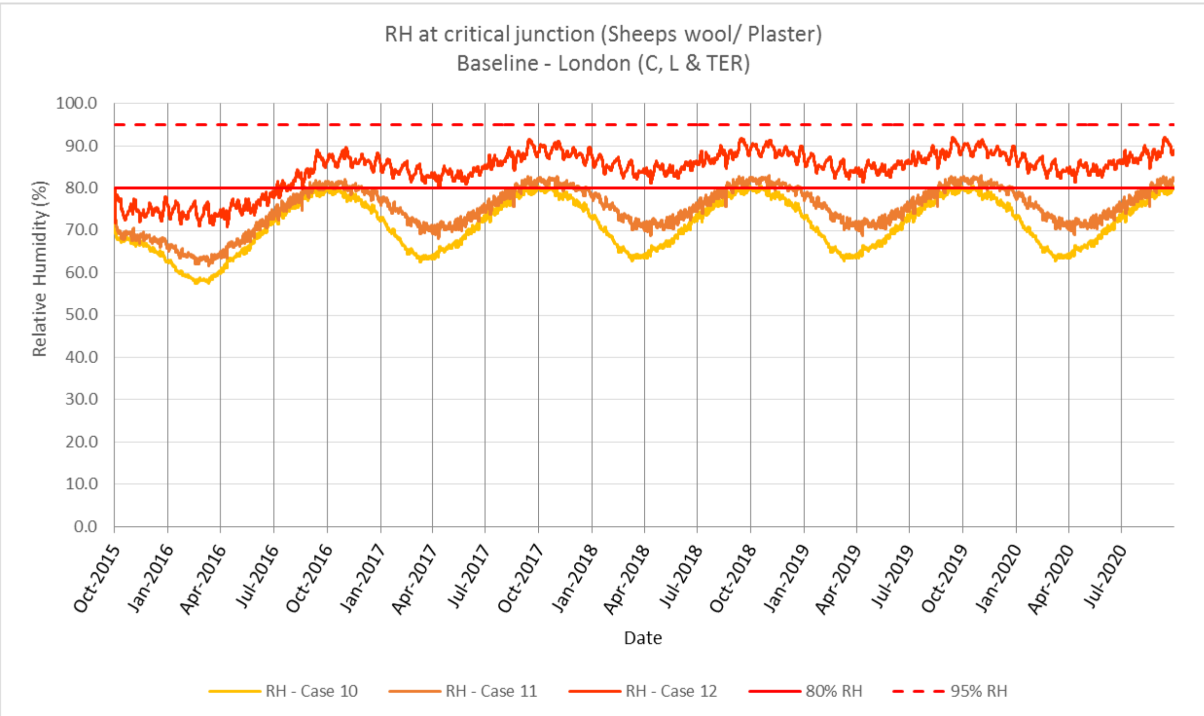


Figure 79: RH levels at critical junction for exposure zone 1

17.3.4. Results Analysis

Moisture risk assessment criteria

The 80% RH threshold can be considered for relaxation to 95% for this critical junction. Although the build-up does not strictly meet the four required criteria set out by WTA, 2009 (see section 2.3), insofar as the second criteria "use of renders, rain-screens or impregnations that prevent driving rain ingress" is not met, since the outer brickwork is exposed. However, the effect of wind driven rain are physically removed from the structural build-up by the presence of the mineral wool cavity insulation. For this reason, results showing the results based on the 95% RH threshold are also shown below.

All exposure zones with the highest levels of insulation have RH levels above 80% constantly after equilibrium is reached.

All exposure zones except exposure zone 2 with Part L levels of insulation have RH levels slightly above 80%, but for periods longer than a month after equilibrium is reached. Zone 2 RH levels are considered high enough to designate the build-up as 'risky'.

All exposure zones with the levels of insulation to reach the Part C requirement have the same profiles as part L but with RH levels below 80% continuously after equilibrium is reached.

Results

Table 37: Summary of results with 80% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Fail	Fail	Risky	Fail
TER	Fail	Fail	Fail	Fail

Table 38: Summary of results with 95% RH threshold

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Pass	Pass	Pass	Pass
Part L	Pass	Pass	Pass	Pass
TER	Pass	Pass	Pass	Pass

Effects of exposure zones

The difference in exposure zones is small but noticeable on the graphs, with build-ups in zones that are more exposed to wind-driven rain displaying on average higher RH levels at critical junctions. This finding is as predicted, since the hygrothermal performance of exposed brick walls is directly affected by the external conditions.

However wind-driven rain exposure zones are not “driving” the status of the cases – as U-values / insulation thicknesses have a much bigger impact of the hygrothermal performance of the build-ups.

Effects of U-value

The most noticeable effect of increasing insulation levels is to shift the peak RH from summer to winter. This tendency is useful since although there are higher peak RH levels for higher levels of insulation , the temperature at this time should be insufficient to encourage mould growth.

As expected with internal wall insulation; the higher the level of insulation, the higher the moisture levels at the critical junction. The levels of insulation required in order to achieve the lower U-value targets is unlikely to be installed in practice since the insulation would be 'too thick' to be practical.

Effects of Brick Physical Properties

The main moisture source creating problems in an exposed wall build-up is rain penetration from the outside. As the external wall, in this build-up, is not protected, moisture (as liquid water) penetrates deeper into the build-up in the winter via capillary action due to wind-driven rain reaching the façade. As both cavity wall and internal wall insulation is installed directly in contact with the wall structure, the cold side of both insulation layers are exposed to the conditions experienced by the inner surface of the brickwork and blockwork respectively.

However, it is worth noting that this baseline modelling is done using the worst case scenario regarding the physical characteristics of the brick material, which means that the build-up’s hygrothermal performance might be improved when ‘better-performing’ bricks (in terms of moisture properties) are used.

17.3.5. Additional Monitored Junction

The critical junction is correctly located in BS 5250 (2011), being the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation.

BS 5250 (2011) also identifies a second interface for cavity walls, which is less at risk but where there might still be a risk for moisture to accumulate, stating: "*Any interstitial condensation which might occur will do so on the inner surface of the external skin, where it is unlikely to cause damage to non-hygroscopic insulation, or insulation which does not fill the cavity.*"

The results are similar to the same monitored junctions for R12 with Wood Fibre IWI and this result is in line with the previous findings from the M7 report, and confirms the previous results as all cases reach equilibrium very quickly. However, all of the cases monitored at the interface between the outer brick leaf and the cavity wall insulation display RH levels well above 95% and reaching 100% (i.e. interstitial condensation) up to several months a year.

In addition, RH levels are still above 80% throughout the year (including the summer season, when temperatures are high enough to promote mould growth). The subject of buildability with cavity walls has also been raised with the R12 typology (full-fill cavity wall). It is possible for a small air gap to be present in between the outer brickwork layer and the insulation for diverse buildability reasons (insulation being squashed and not expanding through the whole cavity, insulation not being thick enough, etc.). It is also likely for mould growth to find a food source (even if not abundant), which means all the conditions for mould growth could be met at this interface.

As mentioned before, the risk was highlighted in paragraph G.4.2.3 in BS 5250 (2011) but the guidance also mentions that it should not lead to any damages provided these risks are well taken into account and dealt with (with the use of non-hygroscopic materials and provision to allow for any accumulated moisture to be drained out of the cavity).

Therefore, if mould growth were to occur, as its location is isolated from the indoor environment, there would be no significant consequences to the build-up or the health of building occupants.

17.3.6. Conclusions – Baseline

- Build-up hygrothermal performance is linked to exposure zone: the more exposed the build-up is, the higher the RH levels experienced although all cases show up to 100% RH leading to interstitial condensation on the inner surface of the outer brickwork
- Presence of interstitial condensation, though not a significant issue as interstitial condensation accounted for and interstitial condensation removal process included in build-up
- Question about thermal conductivity (+ thermal performance) of insulation when constantly submitted to high RH levels (> 80%)
- Risk of mould growth behind internal wall insulation probably worsened for ‘non-perfect’ build-up in practice (ABIS conditions), which could mean the presence of food and air for mould growth and direct contact with the internal environment, so not recommended on the inner surface of the insulation).

<u>STBA / DECC's guidance</u>
‘There is the possibility that the insulation will bridge the cavity allowing moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair and the insulation has been properly installed, the risk is negligible, except in conditions of extreme driven rain‘

(This is an extract from the STBA / DECC's guidance, which is the latest guidance on this build-up. It is suggesting that this build-up is safe except in extreme driven rain (i.e. Zone 4) and therefore conclusion to include and compare our findings with this guidance.

Prolonged rain has been predicted as part of the climate change. Since more rainfall is likely to mean more wind-driven rain, it may have a greater impact.

18. Appendix A – Exhaustive material list and their respective parameters used in the WUFI modelling

Material	Data Source	Material in standard U-value / WUFI database	WUFI database baseline material for new material	Thickness	Bulk Density	Porosity	Specific Heat Capacity, Dry	Thermal Conductivity, Dry 10°C	Water Vapour Diffusion Resistance Factor	Equiv. Air Thickness	Reference Water Content	Free Water Saturation	Water Absorption Coefficient	Water Absorption Coefficient
				t	ρ_{bulk}	w_{max}	cp	λ	μ	s_d	w80	w_f	A	A
				(mm)	(kg/m3)	(m3/m3)	(J/kg.K)	(W/m.K)	(-)	(m)	(kg/m³)	(kg/m³)	(kg/m²√s)	(kg/m²√h)
1 Timber Joists	3	Timber (softwood)	-	150	500	Ø	Ø	0.13	20	~	Ø	Ø	Ø	Ø
	1	**Softwood**	-	**150**	**400**	**0.73**	**1500**	**0.09**	**200**	~	**60**	**575**	-	-
2 Chip board	3	Chipboard	-	18	600	Ø	Ø	0.14	15	~	Ø	Ø	Ø	Ø
	1	**Chipboard**	-	**18**	**600**	**0.5**	**1500**	**0.11**	**70**	~	**90.0**	**400**	-	-
3 Plywood	3	Plywood	-	9	500	Ø	Ø	0.13	70	~	Ø	Ø	Ø	Ø
	1	**Plywood board**	-	**9**	**500**	**0.5**	**1500**	**0.10**	**700**	~	**75**	**350**	-	-
4 OSB	3	OSB	-	9	650	Ø	Ø	0.13	30	~	Ø	Ø	Ø	Ø
	1	**OSB (density 615 kg/m3)**	-	**9**	**615**	**0.9**	**1500**	**0.13**	**175**	~	**92**	**636**	**0.001**	**0.06**
5 Concrete screed	3	Concrete screed	-	75	1200	Ø	Ø	1.15	60	~	Ø	Ø	Ø	Ø
	1	**Concrete screed (mid layer)**	-	**75**	**1970**	**0.177**	**850**	**1.60**	**69**	~	**8**	**152**	**0.016**	**0.96**
6 Concrete slab	3	Concrete slab	-	150	2000	Ø	Ø	1.35	60	~	Ø	Ø	Ø	Ø
	1	**Concrete (C35/45)**	-	**150**	**2220**	**0.18**	**850**	**1.60**	**248**	~	**8**	**147**	**0.009**	**0.54**
7 Concrete	3	Insitu Concrete	-	102	1800	Ø	Ø	1.15	60	~	Ø	Ø	Ø	Ø
	1	**Concrete (C35/45)**	-	**150**	**2220**	**0.18**	**850**	**1.60**	**248**	~	**8**	**147**	**0.009**	**0.54**
8 Floor Blocks	3	Concrete floor blocks	-	100	660	Ø	Ø	0.16	6	~	Ø	Ø	Ø	Ø
	1	**Concrete blocks (pumice aggregate)**	-	**100**	**664**	**0.67**	**850**	**0.14**	**4**	~	**28**	**291**	**0.047**	**2.82**
9 Blockwork	3	Blockwork - medium aggregate	-	100	1400	Ø	Ø	0.57	10	~	Ø	Ø	Ø	Ø
	5	**Blockwork - medium density**	**Concrete blocks (pumice aggregate)**	**100**	**1450**	**0.43**	**850**	**0.47**	**10**	~	**18**	**219**	**0.028**	**1.68**
10 Gravel	3	Gravel	-	150	1700	Ø	Ø	2	50	~	Ø	Ø	Ø	Ø
	1	**Generic Gravel**	-	**150**	**1400**	**0.3**	**1000**	**0.70**	**1**	~	**5**	**50**	-	-
11 Brick wall	3	Solid brick wall	-	215	1700	Ø	Ø	0.77	45	~	Ø	Ø	Ø	Ø
	1	**Solid brick (hand-formed)***	-	**215**	**1725**	**0.38**	**850**	**0.60**	**17**	~	**2.7**	**200**	**0.300**	**18**
		*In solid brick wall with IWI, we know that the brick characteristics play a major role on the hygrothermal performance of the build-up. A sensitivity analysis will be done and we suggest some of the following bricks from WUFI database:												
	1	Solid brick masonry	-	215	1900	0.24	850	0.6	10	~	18	190	0.110	6.600
	1	Aerated clay brick (650 kg/m3)	-	215	650	0.74	850	0.13	15	~	15	178	0.097	5.820
12 EPS Insulation	3	EPS	-	87.5	15	Ø	Ø	0.04	60	~	Ø	Ø	Ø	Ø
	1	**EPS (density: 15 kg/m3)**	-	**87.5**	**15**	**0.95**	**1500**	**0.04**	**30**	~	-	-	-	-
13 XPS	3	XPS	-	30	30	Ø	Ø	0.03	50	~	Ø	Ø	Ø	Ø
	1	**XPS Surface Skin (heat. cond.: 0.03 W/m.K)**	-	**30**	**40**	**0.95**	**1500**	**0.03**	**450**	~	-	-	-	-
	1	**XPS Core (heat. cond.: 0.03 W/m.K)**	-	**30**	**40**	**0.95**	**1500**	**0.03**	**100**	~				
14 Polyurethane	3	PU Foam	-	30	30	Ø	Ø	0.025	50	~	Ø	Ø	Ø	Ø
	1	**PU (heat cond.: 0.025 W/m.K)**	-	**30**	**40**	**0.95**	**1500**	**0.025**	**50**	~	-	-	-	-
15 Mineral wool	3	Mineral wool	-	100	12	Ø	Ø	0.04	1	~	Ø	Ø	Ø	Ø
	1	**Mineral wool (heat cond.@ 0.04W/m.K)**	-	**100**	**60**	**0.95**	**850**	**0.04**	**1.3**	~	-	-	-	-
16 DPM	3	DPM	-	0.3	920	Ø	Ø	0.17	400000	Ø	Ø	Ø	Ø	Ø
	1	**DPM (sd = 136m)**	**vapour retarder (sd = 100m)**	**1**	**130**	**0.001**	**2300**	**2.30**	**136400**	**136**	-	-	-	-
17 Foil paper facing	3	Foil paper facing	-	0.05	1100	Ø	Ø	200	999999	Ø	Ø	Ø	Ø	Ø
	1	**Foil paper facing (sd = 14m)**	**vapour retarder (sd = 10m)**	**1**	**130**	**0.001**	**2300**	**2.30**	**14000**	**14.0**	-	-	-	-
18 VCL	3	VLC / Polyethylene	-	0.05	920	Ø	Ø	0.17	300000	Ø	Ø	Ø	Ø	Ø
	1	**VLC (sd = 2m)**	**vapour retarder (sd = 2m)**	**1**	**130**	**0.001**	**2300**	**2.30**	**2000**	**2**	-	-	-	-
19 Breather Membrane	3	Breather membrane	-	0.1	350	Ø	Ø	0.17	2000	Ø	Ø	Ø	Ø	Ø
	1	**Breather membrane (sd = 0.04m)**	**weather resistive barrier (sd = 0.1m)**	**1**	**130**	**0.001**	**2300**	**2.30**	**40**	**0.04**	-	-	-	-
20 Gypsum Plasterboard	3	Gypsum plasterboard	-	12.5	700	Ø	Ø	0.21	4	~	Ø	Ø	Ø	Ø

Material	Data Source	Material in standard U-value / WUFI database	WUFI database baseline material for new material	Thickness	Bulk Density	Porosity	Specific Heat Capacity, Dry	Thermal Conductivity, Dry 10°C	Water Vapour Diffusion Resistance Factor	Equiv. Air Thickness	Reference Water Content	Free Water Saturation	Water Absorption Coefficient	Water Absorption Coefficient
				t	ρ_{bulk}	w_{max}	cp	λ	μ	s_d	w80	w_f	A	A
				(mm)	(kg/m3)	(m3/m3)	(J/kg.K)	(W/m.K)	(-)	(m)	(kg/m³)	(kg/m³)	(kg/m²√s)	(kg/m²√h)
	1	**Gypsum board**	-	**12.5**	**850**	**0.65**	**850**	**0.20**	**8.3**	~	**6.3**	**400**	**0.287**	**17.22**
21 Gypsum Plaster	3	Wet plaster	-	12.5	700	∅	∅	0.21	4	~	∅	∅	∅	∅
	1	**Interior Plaster (Gypsum plaster)**	-	**12.5**	**850**	**0.65**	**850**	**0.20**	**8.3**	~	**6.3**	**400**	**0.287**	**17.22**
22 Silicone render	3	Silicone render	-	15	1250	∅	∅	0.3	9.8	~	∅	∅	∅	∅
	2	**Silicone resin finishing coat (Masea database)**	-	**15**	**1475**	**0.44**	**1000**	**0.69**	**74**	~	**2.9**	**303**	**0.000**	**0.01**
23 Render	3	Render (sand and cement)	-	15	1600	∅	∅	0.8	6	~	∅	∅	∅	∅
	1	**Cement plaster (stucco, A = 0.51 kg/m2√h)**	-	**12.5**	**2000**	**0.3**	**850**	**1.20**	**25**	~	**35**	**280**	**0.009**	**0.51**
24 Cement particle board	3	Cement particle board	-	25	1200	∅	∅	0.23	30	~	∅	∅	∅	∅
	2	**Cement board (North American database)**	-	**25**	**1130**	**0.48**	**840**	**0.26**	**28**	~	-	-	-	-
25 Bitumen	3	Bitumen	-	25	110	∅	∅	0.23	50000	∅	∅	∅	∅	∅
	2	**Bitumous felt (Generic database)**	**Roof membrane V13 (sd = 100m)**	**1**	**2400**	**0.001**	**1000**	**0.5**	**100000**	**100.0**	-	-	-	-
26 Unventilated air gap	3	Unventilated air gap - 15mm	-	15	1.2	∅	∅	0.088	1	~	∅	∅	∅	∅
	2	**Air Layer 15mm w/o add. moist. cap. (Generic database)**	**Air layer average (10mm + 20mm)**	**15**	**1.3**	**0.999**	**1000**	**0.10**	**0.65**	~	-	-	-	-
27 Unventilated air gap	3	Unventilated air gap - 50mm	-	50	1.2	∅	∅	0.278	1	~	∅	∅	∅	∅
	2	**Air Layer 50mm w/o add. moist. cap. (Generic database)**	-	**50**	**1.3**	**0.999**	**1000**	**0.28**	**0.32**	~	-	-	-	-
28 Unventilated air gap	3	Unventilated air gap - 100mm	-	100	1.2	∅	∅	0.9	1	~	∅	∅	∅	∅
	2	**Air Layer 100mm w/o add. moist. cap. (Generic database)**	-	**100**	**1.3**	**0.999**	**1000**	**0.59**	**0.15**	~	-	-	-	-
29 Unventilated air gap	3	Unventilated air gap - 200mm	-	100	1.2	∅	∅	0.9	1	~	∅	∅	∅	∅
	2	**Air Layer 200mm w/o add. moist. cap. (Generic database)**	**Air layer assumption (150mm)**	**100**	**1.3**	**0.999**	**1000**	**1.08**	**0.05**	~	-	-	-	-
30 Stone wool Rockwool	-	-	-	-	-	-	-	-	-	~	-	-	-	-
	1	**Stone wool Rockwool RedART**	**Mineral wool**	**100**	**107**	**0.96**	**1030**	**0.036**	**1.1**	~	**0.09**	**150**	**0.00083**	**0.050**
31 Silicone Render Rockwool	-	-	-	-	-	-	-	-	-	~	-	-	-	-
	2	**Silicone render Rockwool RedART**	**Silicone resin finishing coat**	**15**	**1800**	**0.41**	**1500**	**0.70**	**80**	~	**3.1**	**350**	**0.00019**	**0.011**
RETROFIT														
32 Lime Plaster	1	-	-	-	-	-	-	-	-	~	-	-	-	-
	1	**Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)**	-	**15**	**1600**	**0.3**	**850**	**0.70**	**7**	~	**30**	**250**	**0.05**	**3**

\# Data sources

1 - Fraunhofer IBP database in WUFI
2 - Other Database in WUFI
3 - Estimated based on standard materials (i.e. Builddesk)
4 - Manufacturer information
5 - Adapted from manufacturer literature
6 - Estimate based on industry literature

19. Appendix B – Glossary

Accredited construction detail	Junction details developed to assist the construction industry achieve the performance standards required to demonstrate compliance with the energy efficiency requirements (Part L) of the Building Regulations. They focus on thermal bridging (i.e. avoiding extra heat loss at the junctions of insulted elements) and the consequential risk of surface condensation / mould growth. They are not designed to address interstitial condensation.
Adhering fraction of rain	Ratio of available rain fall penetrating the external surface of an element over the total amount of rain fall. It takes into account that some of the rain water hitting the component surface splashes off on impact and might not be available for capillary absorption (it varies from zero if the facade is protected from rain, 0.7 for an exposed wall and 1 if all rain water shall be available for absorption, flat roof)
As-Built / In-Service (ABIS) conditions	ABIS conditions describe conditions to which a build-up is submitted, which occur in the real world and take into account the existing or likely-to-exist conditions in buildings, as opposed to a partial risk assessment “as designed” or “theoretical”(ADT), which excludes these ABIS conditions
Building fabric	Elements of the external building envelope (consisting of the building’s roofs, floors, walls, windows and doors), being the separation between the internal environment and the external conditions. It is a critical component of any building, since it both protects the building occupants and plays a major role in regulating the indoor environment.
Condensation	Process whereby water is deposited from air containing water vapour when its temperature drops to or below the dew point (or the vapour pressure rises above the saturated vapour pressure at a given temperature).
Connective effects	Moisture or thermal related effects that occur at interfaces/junctions between elements or materials
Convective transport	Collective motion of water molecules in a fluid (encompassing both diffusion and advection). Convective heat transfer is one of the major types of heat transfer, with convection being a major mode of mass transfer in fluids.
Critical junction	The intersection within a build-up that is the most at risk of interstitial condensation and/or mould growth

Diffusion	The net movement of water molecules from high concentration to low concentration
Equilibrium	An object reaches ***moisture equilibrium*** with the environment when it neither gains nor loses moisture over a set period of time (typically a year) from the constant, dynamic exchange of moisture with the environment
Fragile material	Material that is susceptible to damage (e.g. rot, dimensional instability, surface mould) due to high moisture levels
Glaser method	A simplified one-dimensional steady-state assessment method, described in BS EN ISO 13788, to calculate the amount of interstitial condensate formed during a cold winter period and the theoretical amount of evaporable water in a cold summer. If the amount of condensate does not exceed specified limits and, if it is lower than the evaporable amount of water, the building assembly is considered to be safe.
Ground moisture	Moisture contained in a ground material (e.g. soil), as opposed atmospheric moisture or rain.
Hygroscopic material	A material attracts and hold water molecules from the surrounding environment
Hygrothermal	Relating to the movement of both heat and moisture
Internal Surface Temperature Factor (f_{Rsi})	The ratio of the total thermal resistance of the building envelope to the thermal resistance of the building envelope without the internal surface resistance as defined in EN ISO 10211. Depends on the indoor and outdoor air temperatures and on the temperature at the internal surface of the building envelope. Also referred to as the temperature ratio, temperature index, or condensation resistance factor. In this report, f_{Rsi} is used to indicate the risk of mould growth in indoor environments
Interstitial condensation	Condensation occurring within or between layers of construction elements that are part of a building's thermal envelope.
Masonry walls	Wall made of concrete blocks, stone or brick and mortar
Membranes	A thin pliable sheet of material which forms a barrier, covering or lining
Micro-climates	The climate of a very small or restricted area, especially when this differs from the climate of the surrounding area
Moisture-open	A description for a building material or element that allows water vapour to pass through it without significant barriers.

Moisture Risk Assessment Criteria	Criteria used for assessing the risk of moisture in a building element
Moisture storage function	A curve (approximated in WUFI) for porous hygroscopic materials that defines the way a material absorbs, stores and redistributes water relative to the moisture conditions in the material (relative humidity and total water content)
Porosity	The measure of the void (i.e. "empty") spaces in a material, and is a fraction of the volume of voids over the total volume. Value expressed as a ratio (between 0 and 1), or as a percentage (between 0 and 100%)
Precipitation	Any product of the condensation of atmospheric water vapour that falls under gravity (e.g. rain)
Relative humidity	The ratio of the vapour pressure in air at a given temperature to the saturation vapour pressure at the same temperature; commonly expressed as a percentage (between 0 and 100%).
s_d-value (equivalent air layer thickness)	A measure of the vapour resistance of a material expressed as the thickness which a stagnant air layer would need in order to have the same diffusion resistance. As its name suggests, it is measured in metres. Like vapour resistance, it can only be quoted for a particular thickness of a material.
Solar radiation	Radiant energy emitted by the sun that provides heat energy to exposed objects including building elements.
Specific heat capacity	The property of a material, which measures the energy required to raise the temperature of 1kg of that material by 1°C measured in joule per kelvin J/K.
Surface condensation	Condensation occurring on interior surfaces of a building.
Surface heat transfer coefficients	Thermal resistance of a surface (internal or external) expressed in m2.K/W. Values that are used in conjunction with building material properties (material thermal conductivity and thickness) to calculate the U-value of building elements.
Synthetic weather files	Hourly weather files used for WUFI simulation created from monthly climatic averages using Meteonorm software. Although Meteonorm provides precipitation data, the synthetically derived rain data may have limitations for hygrothermal (WUFI) modelling.
Thermal bypass	Where heat is transferred via convection in a building element due to air gaps within or between materials/components (including cavities). This air

	movement bypasses the normally expected heat transfer mechanisms (used to calculate U-values) and reduces the effective thermal performance of that building element.
Thermal conductivity	The property of a material that describes its ability to conduct heat. Measured in watts per meter kelvin (W/(m·K)). Used, along with a material's thickness, to calculate U-values
U-value	A measure of thermal transmittance, which describes how effective an element of building fabric is as a heat insulator. The lower the U-value, the better the construction is as an insulator. U-values are measured in watts per square metre of surface element per degree Kelvin (W/m^2K).
Vapour Control Layer (VCL)	A material with high vapour resistance (there are varying definitions of this) that reduces/prevents vapour diffusion through a building element.
Vapour diffusion	The physical process of water vapour (not liquid water) passing through porous building materials due to the difference in vapour pressures (water content of the air) on either side on that material.
Vapour resistance	A measure of a material's resistance to letting water vapour pass through. The vapour resistance takes into account the material's thickness, so can only be quoted for a particular thickness of material. It is usually measured in MNs/g ("MegaNewton seconds per gram"). See also s_d Value
Water absorption coefficient A-value	Defined in DIN 52617: "Determination of the water absorption coefficient of building materials". Measured in $kg/m^2s^{1/2}$. For hygroscopic, capillary active materials (such as masonry) the A value provides a reasonable means of estimating how the material absorbs and stores liquid water over time.
Water content	The quantity (mass) of water contained in a material
Wind-driven rain	Rain that is given a horizontal velocity component by the wind otherwise known as "driving rain". Exposure to wind driven rain in the UK is assessed using BS 8104: 1992 – 'Assessing exposure of walls to wind-driven rain'. This standard provides a driving rain index measured in litres per m^2 façade area per spell and also has an exposure map with four zones as follows: • Zone 1 – sheltered – less than 33 l/m2 per spell • Zone 2 – moderate – 33 to less than 56.5 l/m2 per spell • Zone 3 – severe – 56.5 to 100 l/m2 per spell

	• Zone 4 – very severe – 100 l/m2 per spell, or more.
WUFI (Wärme und Feuchte instationär - Transient Heat and Moisture)	Software developed by the Fraunhofer Institute of Building Physics (IBP) in Germany and implements the approach set out in BS EN 15026. It allows realistic calculation of the transient hygrothermal behaviour of multi-layer building components exposed to natural climate conditions and has been validated using data derived from outdoor and laboratory tests. WUFI is based on the newest findings regarding vapour diffusion and liquid transport in building materials. The modelling in this report was carried out with WUFI Pro 5.3, one-dimensional hygrothermal simulation software.

20. Appendix C – References

BS 5250 (2011): Code of practice for control of condensation in buildings. BSI Standards Publication.

BS EN 15026 (2007): ‘Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulation’. BSI Standards Publication.

BS EN ISO 10211 (2007): Thermal bridges in building construction - heat flows and surface temperatures - detailed calculations. BSI Standards Publication.

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