Ministry of Housing,
Communities &
Local Government

Research into resistance to moisture in buildings

Using numerical simulation to assess moisture risk in retrofit constructions. Part 1

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

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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 1** report of the Research into resistance to moisture in buildings project.

There is a **Using numerical simulation to assess moisture risk in retrofit constructions. Part 1** report, which investigates some internal wall insulation build-ups in further detail.

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 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 used for this detailed analysis are listed in the sub-sections below, as explained in the Moisture Risk Assessment and Guidance document by Sustainable Traditional Buildings Alliance (STBA) and Department of Energy & Climate Change (DECC) (2014). 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.

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:

- Moisture must not accumulate over time
  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.

- 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
  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.

- RH levels should drop below 80% within the first six months of simulation
  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

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 multi-dimensional thermal modelling and 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. Internal Surface Temperature Factor f_{Rsi}

The internal surface temperature of a building envelope is directly linked to whether surface condensation and mould growth will occur. Surface condensation will occur when surface RH levels reach 100% on the surface of the element, whereas mould growth will occur when surface RH levels are kept high (typically higher than 80% for typical construction materials).

The internal surface temperature factor f_{Rsi} is used as a risk indicator for mould growth, and is effectively a ratio of the internal surface temperature to the external air temperature (see equation below):

$f_{Rsi} = (T_{si} – T_e) / (T_i – T_e)$
where:

- T_{si} = internal surface temperature (°C)
- T_i = internal temperature (°C)
- T_e = external temperature (°C)

Information Paper IP1/06: *'Assessing the effects of thermal bridging at junctions and around openings'* (2006) gives guidance on minimum critical temperature factors to avoid mould growth on surfaces (around thermal bridge junctions for instance), a minimum f_{Rsi} of 0.75 is recommended for consistently heated buildings such as dwellings, residential buildings and schools.

For an internal temperature of 20°C and an external temperature of 0°C, meeting the minimum f_{Rsi} of 0.75 corresponds to having a minimum internal surface temperature of 15°C to avoid the risk of mould growth.

2.4.2. 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.

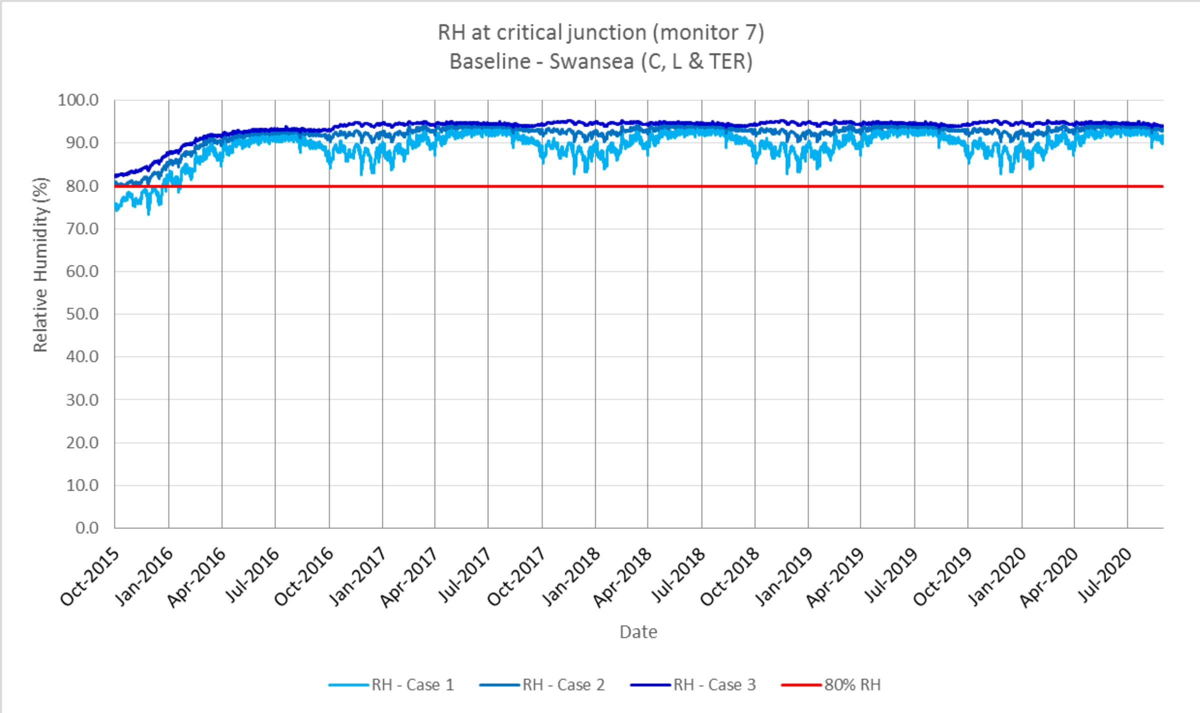


Figure 1: An example of an output graph for displaying RH at critical junction

2.4.3. Graphs: Water Content in Layers

In some particular cases, the water content present in certain layers will also be analysed. This analysis is related to the first moisture risk assessment criteria (as described in section 2.3) which states that moisture should not accumulate over time.

In the layer chosen for assessment, the water content is displayed on the y-axis (in kg/m^3) on a time-based graph (again the 5-year modelling period in this case), as shown in Figure 2.

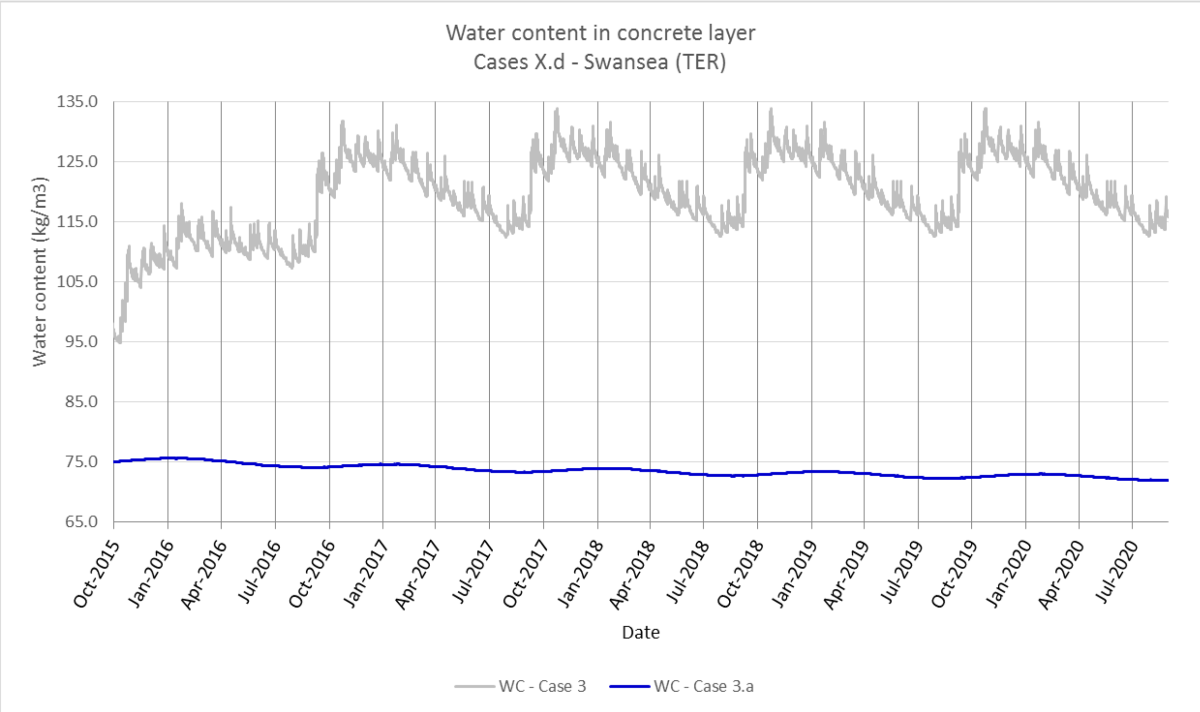


Figure 2: An example of an output graph for displaying water content in a particular layer

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 makes the interpretation of the results more difficult), 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.

Material types and thicknesses have been matched with Glaser simulated build-ups that were presented in the *Using calculation methods to assess surface and interstitial condensation* report.

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

The following inclinations are used, depending on each element type:

- Floor: 0 degrees
- Wall: 90 degrees
- Pitched roof: 35 degrees
- Flat roof: 2 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	Downward	Horizontal	Upward
Rsi (internal)	0.172 m^2.K/W	0.131 m^2.K/W	0.099 m^2.K/W
Rse (external)	0.058 m^2.K/W	0.058 m^2.K/W	0.053 m^2.K/W

3.3.2. Adhering Fraction of Rain

Default values for adhering fraction of rain are used in the modelling, due to lack of standard protocol.

- Adhering fraction of rain – Exposed wall = 70%
- Adhering fraction of rain – Exposed roof = 100%
- 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 for each material. 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, concrete or screed).

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.

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). 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 3 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.

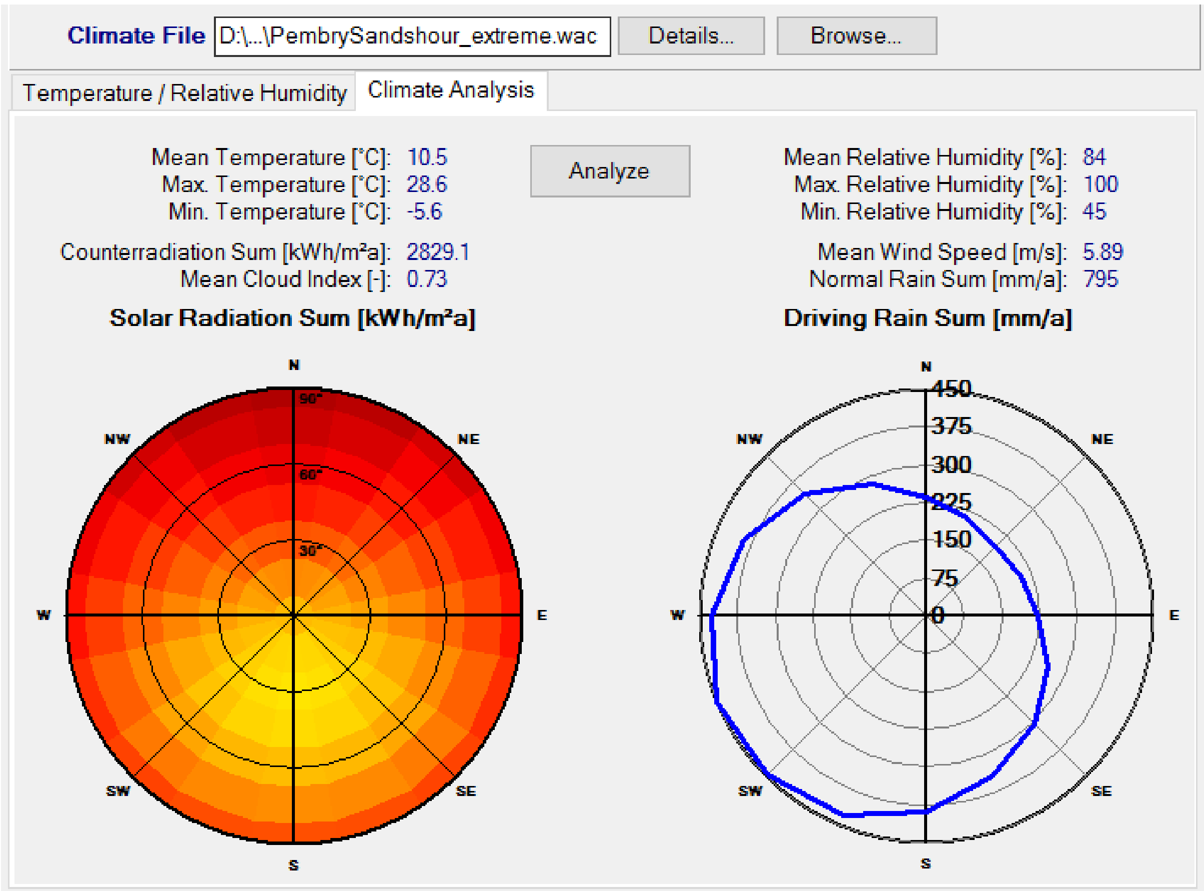


Figure 3: A snapshot of the weather file analysis from WUFI

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 4 and Figure 5:

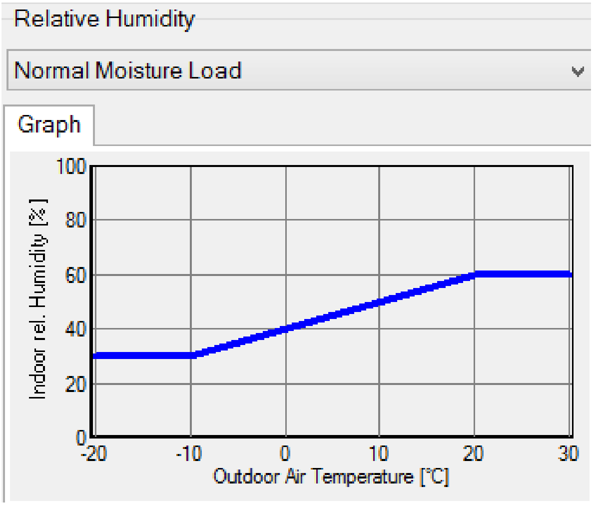


Figure 4: Normal moisture load

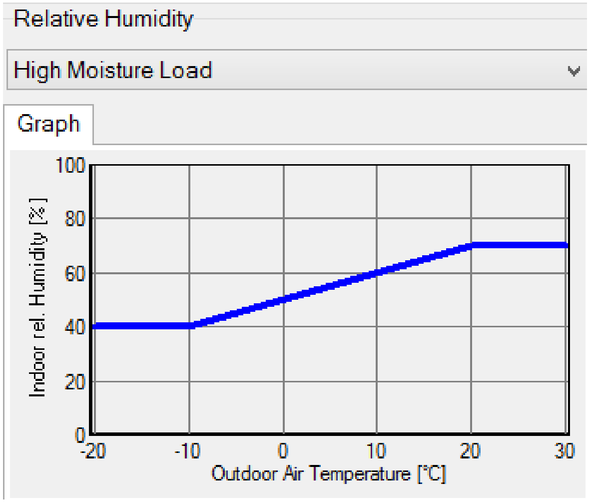


Figure 5: High moisture load

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 *Using calculation methods to assess surface and interstitial condensation* 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**
Floors	0.70	0.25	0.13
Walls	0.70	0.35	0.18
Roofs	0.35	0.25	0.13

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).

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:

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

- Change in external surface performance = Cases X.b
  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.

- Change in orientation = Cases X.c
  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

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

- Other changes = Cases X.e
  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. THERM Model Input Parameters

5.1. Geometry

5.1.1. All junction models are constructed following guidance from Multi-dimensional Thermal Modelling to BS EN ISO 10211 (2007, with the exception of window frames (see below).

5.1.2. Simplified Multi-dimensional Thermal Modelling to BS EN ISO 10077 (2006)

Where junctions incorporate window frames it is not necessary to follow a detailed methodology for glazing and frames since these elements can be simplified without material effect on the surface temperatures at the modelled junction. Therefore the effect of extra heat losses appearing around window junctions can be analysed with multi-dimensional thermal calculations using the methods specified in *BS EN ISO 10077-1 (2006) 'Thermal performance of windows doors and shutters - Calculation of thermal transmittance'.*

5.2. Materials

5.2.1. General

Materials used in THERM analysis are as closely matched to the materials used in the WUFI analysis, with the critical material value being thermal resistance.

Some materials require more detailed treatment, specifically brick layers.

5.2.2. Brick

Where an external brick is modelled as part of a wall structure the thermal resistance of the brick is modified to reflect the exposure of the brick (similarly to adjustments made in U-value calculations)

Brick Exposure	Description of situation	Thermal resistance (λ) (W/mK)
Wet	Below DPC	1.0
Exposed	External skin of wall	0.77
Protected	Inner leaf or behind retrofit EWI	0.56

5.2.3. Air gaps

Thermal resistance of unventilated airspaces have been nominally calculated using the formulas from Appendix B of *BS EN ISO 6946 (2007) Building components and building elements - Thermal resistance and thermal transmittance* - Calculation method. For large spaces the calculation has been made utilising information from Table B.2 from *BS EN ISO 6946 (2007)*.

5.3. Boundary Conditions

5.3.1. Internal

Internal temperature is modelled at 20^{o}C.

5.3.2. External

Suspended floor crawl space - Since a specific building is not being modelled a typical underfloor temperature of 3.2^{o}C is assumed.

Unheated space - Sheltered spaces, e.g. unheated garages, are assumed to have a temperature of 6^{o}C. Since the Internal Surface Temperature Factor (f_{Rsi}) will be higher in value when a lower external temperature is used, this is considered to be a suitably conservative assumption.

6. WUFI Modelling - Construction Types

The most common construction typologies have been chosen for the WUFI analysis, as shown in the table below. Results and analysis are included in Sections 7 to 29.

Table 5: Retrofit Typologies analysed

	Construction Type
R1.1	Suspended timber floor (uninsulated) Retrofit Measure: insulation between the joist
R1.2	Suspended timber floor (uninsulated) Retrofit Measure: insulation above
R2	In-situ ground bearing concrete floors (uninsulated) Retrofit Measure: insulation above
R4	Beam and block ground floors Retrofit Measure: Insulation added above
R5.1	Exposed floors – suspended timber floor Retrofit Measure: insulation between and below joists
R5.2	Exposed floors – suspended timber floor Retrofit Measure: insulation below
R6	Exposed upper floors - concrete (uninsulated) Retrofit Measure: insulation above
R7	Exposed floors - concrete (uninsulated) Retrofit Measure: insulation below
R8	Solid masonry wall Retrofit Measure: Internal Wall Insulation (IWI)
R9	Solid masonry Retrofit Measure: External Wall Insulation (EWI)
R11.1	Cavity masonry (uninsulated) Retrofit Measure: Internal Wall Insulation (IWI)
R11.2	Cavity masonry (uninsulated) Retrofit Measure: External Wall Insulation (EWI) and Cavity Wall Insulation (CWI)
R11.3	Partial-fill cavity masonry Retrofit Measure: Internal Wall Insulation (IWI)
R12	Full-fill cavity masonry Retrofit Measure: Internal Wall Insulation (IWI)
R14.1	Framed building (timber framed) Retrofit Measure: External Wall Insulation (EWI)
R14.2	Framed building (timber framed) Retrofit Measure: Internal Wall Insulation (IWI)
R17	Cold pitched roof - insulated at ceiling level Retrofit Measure: Additional insulation above timber joists
R18.1	Warm pitched roof - uninsulated Retrofit Measure: Insulation below rafters
R18.2	Warm pitched roof - uninsulated Retrofit Measure: Insulation between and below
R19	Warm flat timber roof Retrofit Measure: insulation above

	Construction Type
R20	Cold flat roof Retrofit Measure: insulation below
R21	Warm flat concrete roof Retrofit Measure: insulation above
R22	Inverted flat concrete roof Retrofit Measure: insulation above

7. Typology R1.1: Suspended timber floor (uninsulated) Retrofit Measure: insulation between the joist

The R1.1 typology is a suspended timber floor that is uninsulated prior to retrofit. The retrofit measure is to install insulation between the timber joists.

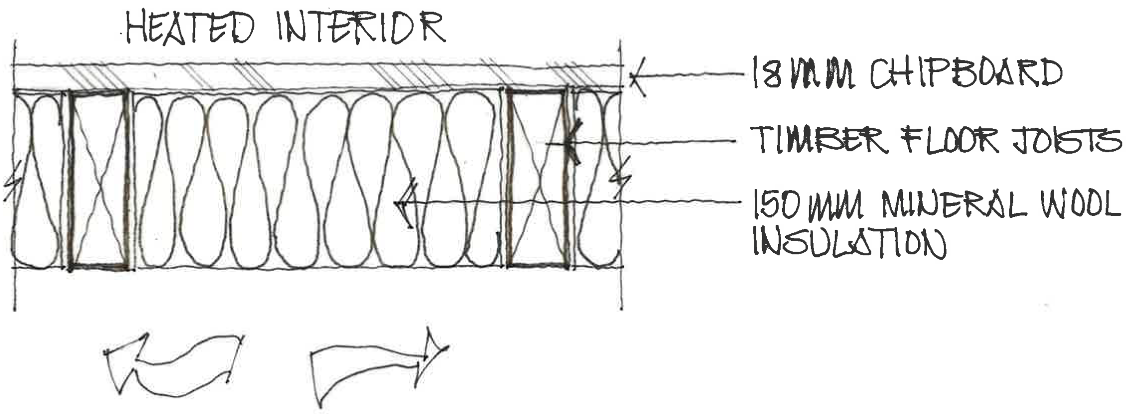


Figure 6: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

7.1. Build-up

7.1.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 18mm chipboard
- 150mm uninsulated timber joists (above ventilated air space)

7.1.2. WUFI Build-up (post-retrofit)

Build-Up:

- 18mm chipboard
- 150mm mineral wool insulation ((λ = 0.040 W/m.K) installed in between existing timber joists

The build-up of R1.1 is identical to the Part L case in N1 of *Using numerical simulation to assess moisture risk in new constructions* report (Suspended floor - insulated) with a slight variation in the thickness of the insulation layer. As this modelling work is assessing qualitatively the impact of different measures on the hygrothermal performance of each typology, this slight difference in insulation thickness does not have any consequential effect on the results.

The only other difference between the two typologies is the timing of the installation of the insulation layer. For N1, the insulation between the joists is installed simultaneously to the rest of the floor construction; whereas for R1.1, the insulation is retrofitted between the existing floor joists.
As part of the WUFI modelling process (in Section 3.4 of this report), a pre-retrofit build-up is supposed to be run to determine equilibrium levels. However, the pre-retrofit build-up for R1.1 is an uninsulated suspended timber floor. The materials present in the pre-retrofit build-up are not exposed to wind-driven rain and are not heavy weight materials. Therefore, it is not 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.

As no equilibrium model is required for R1.1, the initial conditions in the R1.1 WUFI model are identical to the N1 WUFI model. As a result, both R1.1 and N1 have the same WUFI input data and therefore share the same results, despite the difference in the timing of the installation of the insulation layer. For these reasons, no baseline or sensitivity modelling is performed on this typology, please therefore refer to the *Using numerical simulation to assess moisture risk in new constructions* Report for the results and analysis of typology N1 (Section 5).

8. Typology R1.2: Suspended timber floor (uninsulated) Retrofit Measure: insulation above

The R1.2 typology is a suspended timber floor uninsulated prior to retrofit. The retrofit measure is to install insulation and new floor above the existing floor.

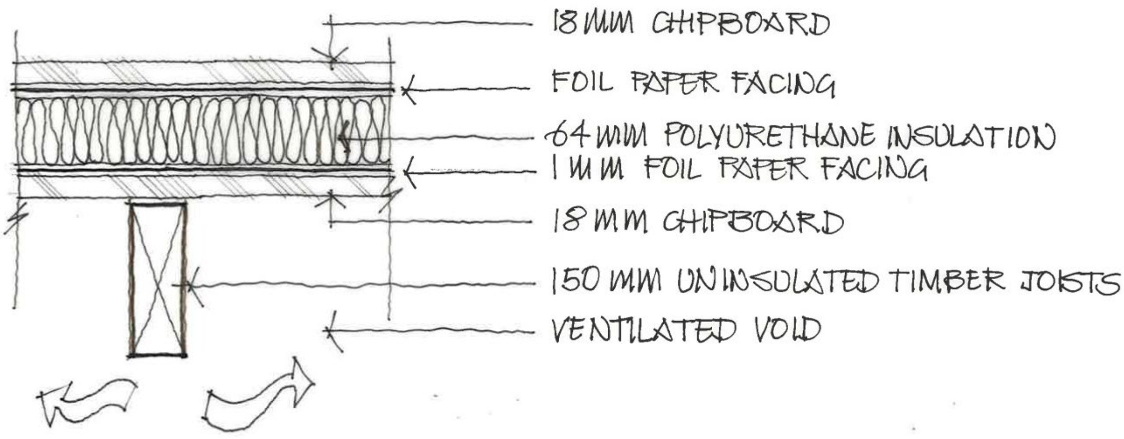


Figure 7: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

8.1. Assessment Method

As described in the STBA /DECC's Moisture Risk Assessment and Guidance (2014), *'floors of timber with a void beneath them should be ventilated to remove moisture'.* To follow prescriptive guidance in section F.4.3 of BS 5250 (2011), the void is ventilated to outside, meaning that the external surface of the build-up is not exposed directly to rain, wind and solar radiations. Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method, as the main process driving moisture transfer in this build-up is vapour diffusion and the build-up is not exposed to wind-driven rain.

The results from the Glaser method analysis show that the post-retrofit build-up is considered to be a 'safe' build-up, with interstitial condensation occurring during the winter season, but evaporating completely during the summer months. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

However, the section F.4.3 of BS 5250 (2011) also states that *'when thermal insulation is applied above the joists, there is a risk of interstitial condensation occurring on the timber. To avoid such condensation, an AVCL should be laid between the thermal insulation and the floor finish'*.

8.2. Build-up

8.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 18mm chipboard
- 150mm uninsulated timber joists (above ventilated air space)

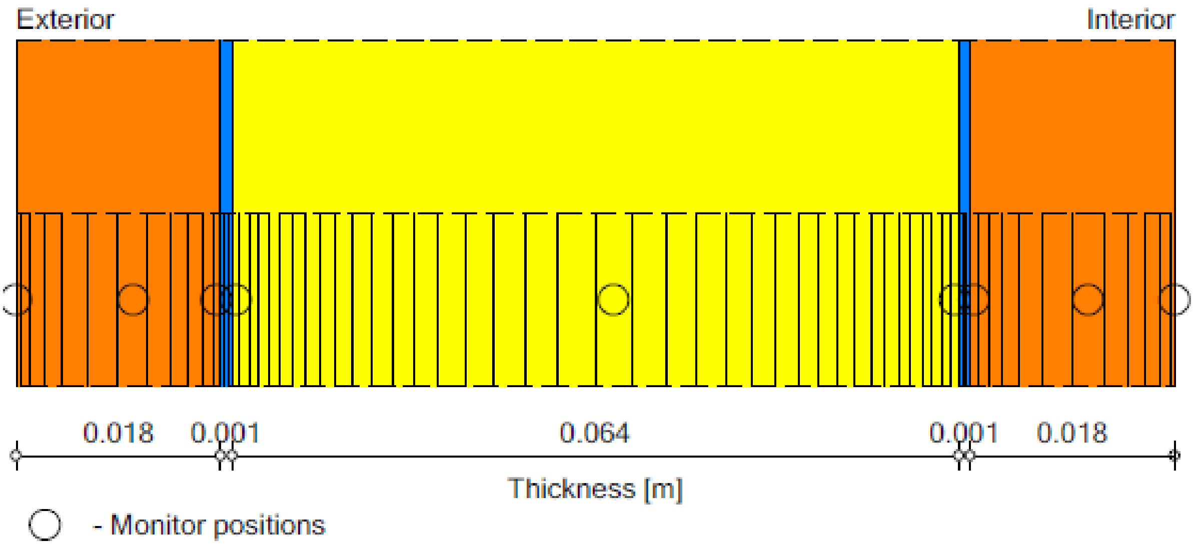
8.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are not exposed to wind-driven rain and are not heavy weight materials. Therefore, it is not 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)

Build-Up:

- 18mm chipboard
- 1mm foil paper facing (sd = 14m)
- 64mm polyurethane insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 18mm chipboard
- 150mm uninsulated timber joists *(considered outside of the WUFI build-up)*



Materials:

- *Chipboard 0.018 m
- *Foil paper facing (sd = 14m) (unlocked) 0.001 m
- *PU (heat cond.: 0,025 W/mK) 0.064 m
- *Foil paper facing (sd = 14m) (unlocked) 0.001 m
- *Chipboard 0.018 m

In many cases, such a deep thickness of retrofit insulation may be impractical to install, since the interaction between the raised floor level and doors (as well as around stairs) may result in conflicting requirements. As this work is generic (no specific retrofit case), the insulation thickness was chosen to match the Part L1B U-value requirement.

WUFI Input Parameters

As the crawl space is considered ventilated, the uninsulated timber joists 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 external chipboard) is exposed to different external conditions due to the crawl space acting as a protective layer against wind-driven rain.

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
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)

8.3. Baseline Results

8.3.1. Baseline Cases

The 4 baseline cases are set across the four wind-driven rain exposure zones, meeting the Part L target U-value, as set out below.

Table 6: 4 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

8.3.2. Critical and Monitored Junctions

As mentioned previously, the build-up is protected from rain, wind and solar radiation, and should not present any moisture risks (as shown in the BS EN ISO 13788 (2012) calculations). However, as mentioned in section F.4.3 of BS 5250 (2011), the focus is given on the RH levels at the interface between the external chipboard floor and the insulation layer (i.e. on the cold side of the insulation). This critical junction is correctly identified in the BS EN ISO 13788 (2012).

However, the insulation also has a foil layer present which presents a significant barrier to moisture movement at this interface. As vapour transfer mainly occurs through vapour diffusion in this build up (i.e. from inside to outside in winter season), the foil layer significantly reduces the possibility of moisture accumulation at the critical interface previously mentioned. Therefore, RH levels are safer at the critical junction (i.e. between the external chipboard layer and the foil layer) than on the other side of the foil layer (i.e. between the foil layer and the insulation layer). As such, the results from an additional monitor, on the other side of the foil layer, need to be examined to get a clearer picture of the potential risks at this junction.

The critical level of 80% has been maintained in both positions.

8.3.3. Graphs at Critical and Monitored Junctions

The graphs displayed below show the RH levels for each location at the two critical / monitored junctions:

- The interface between the external chipboard layer and the foil layer (listed as monitor 3 here)
- The interface between the foil layer and the insulation (monitor 4)

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).

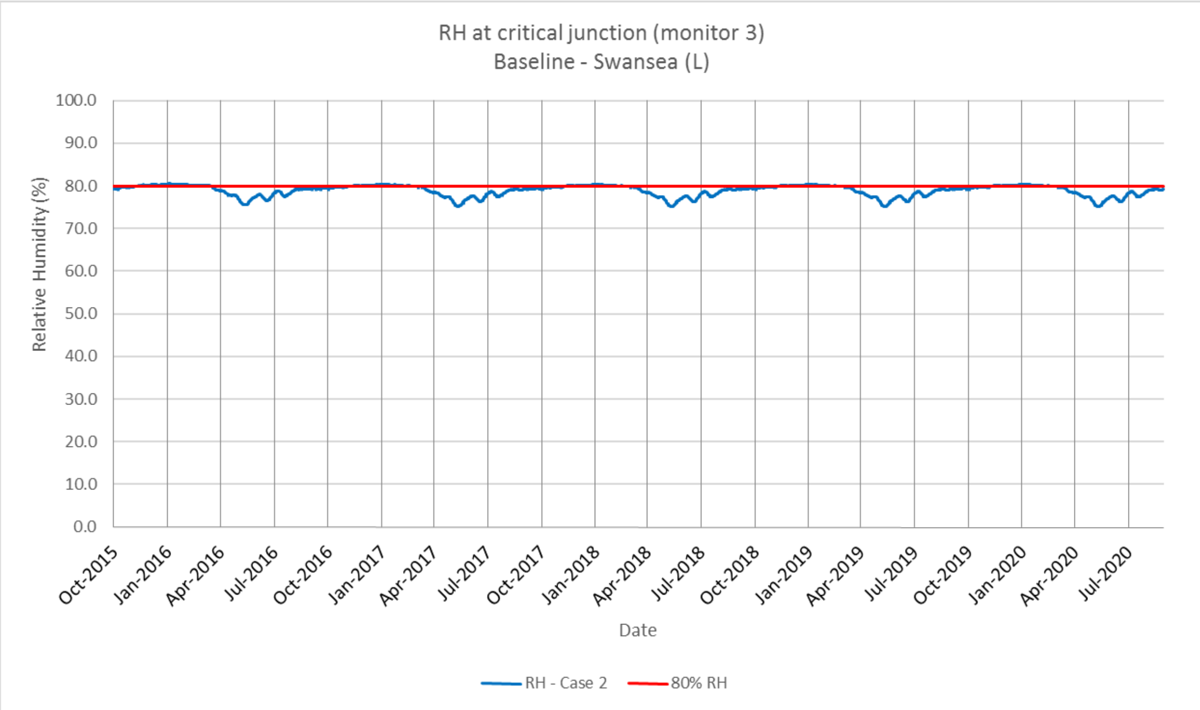


Figure 8: RH levels at monitored junction 3 for Case 2

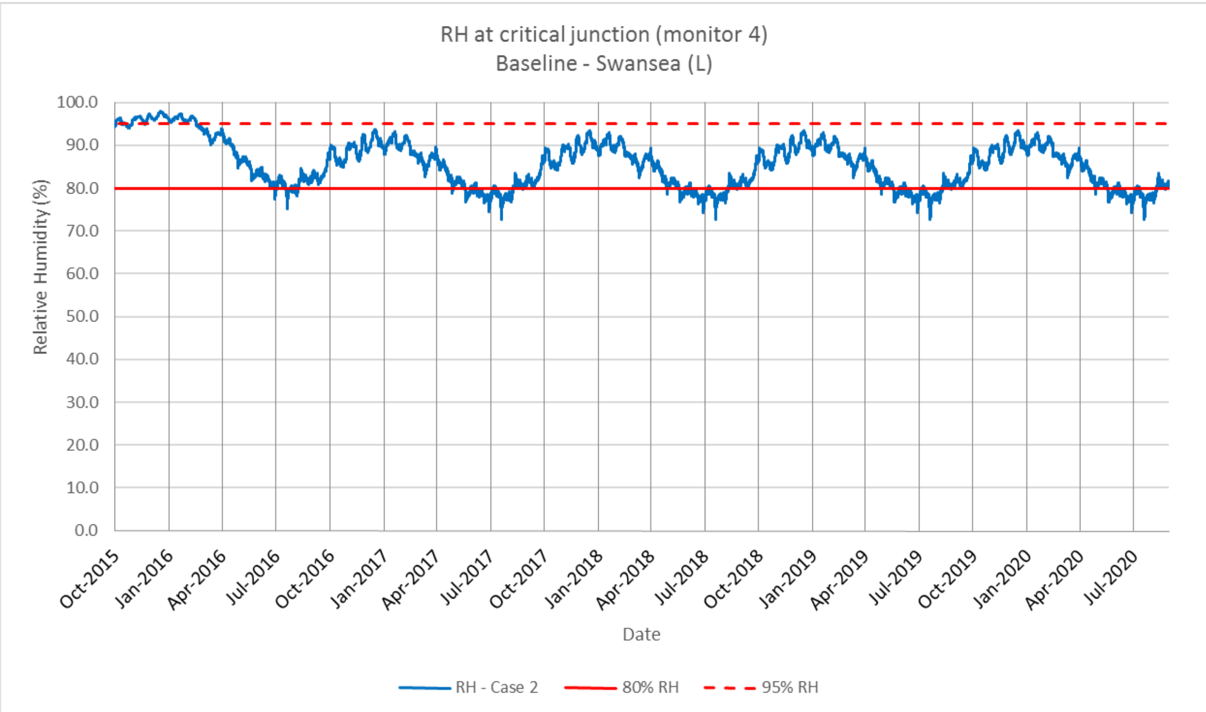


Figure 9: RH levels at monitored junction 4 for Case 2

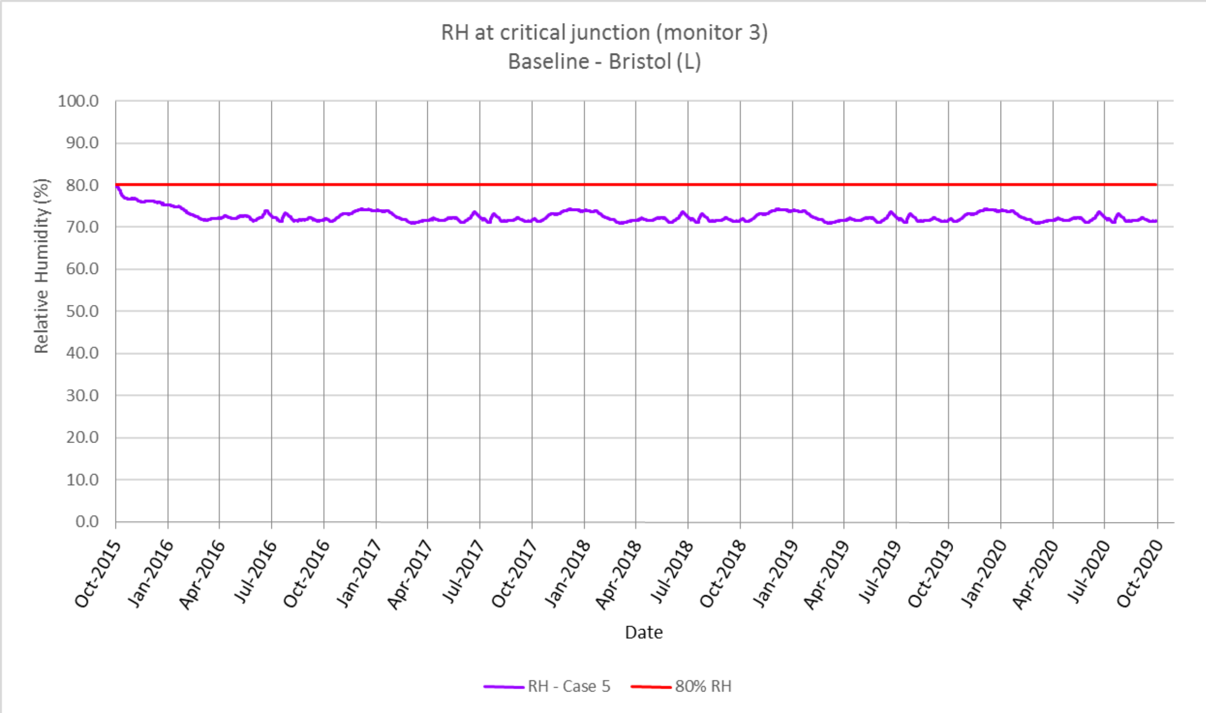


Figure 10: RH levels at monitored junction 3 for Case 5

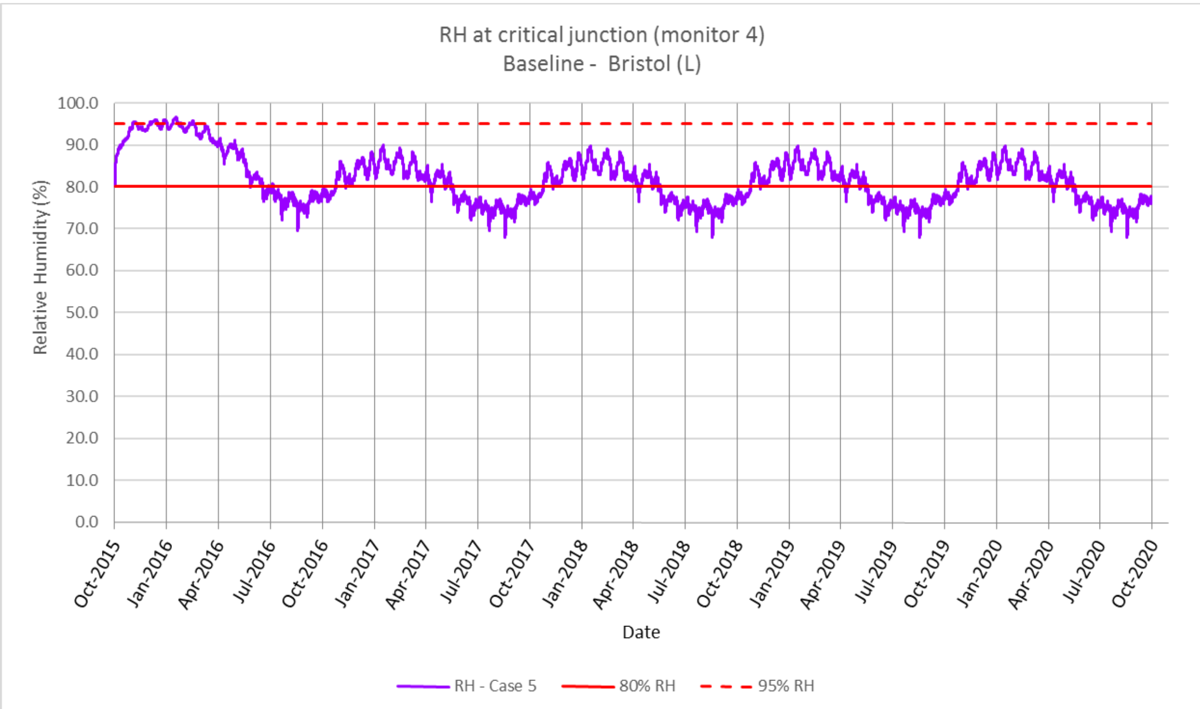


Figure 11: RH levels at monitored junction 4 for Case 5

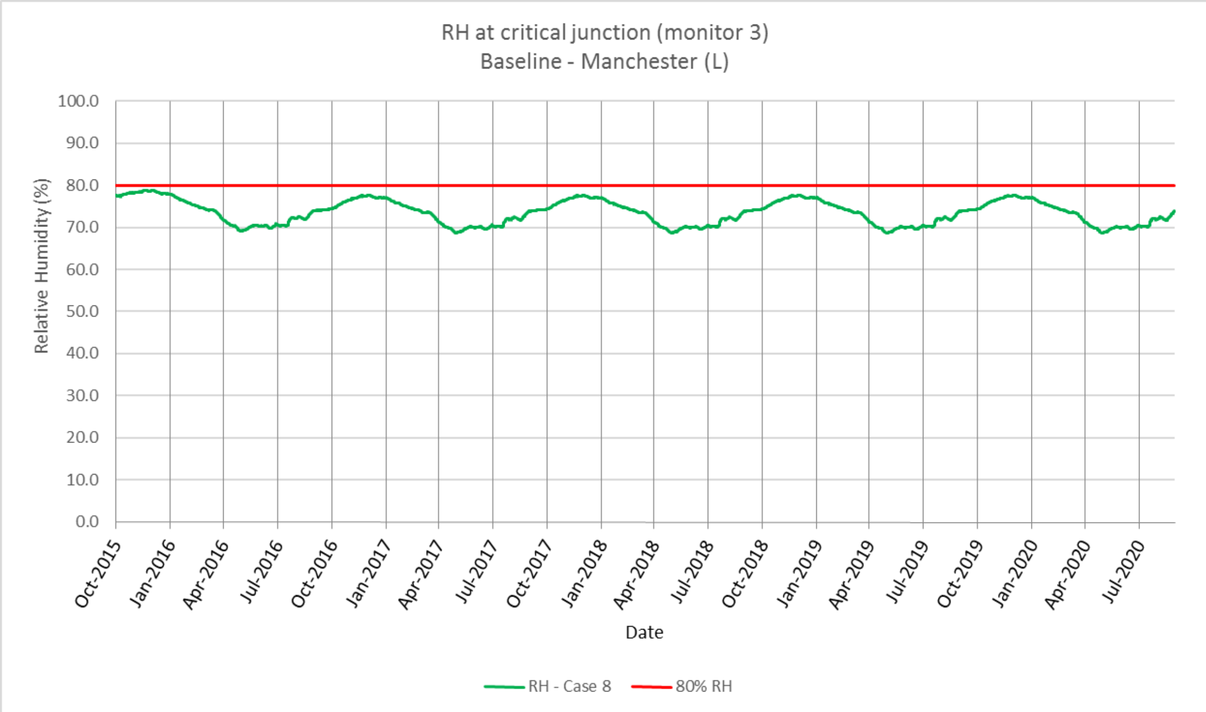


Figure 12: RH levels at monitored junction 3 for Case 8

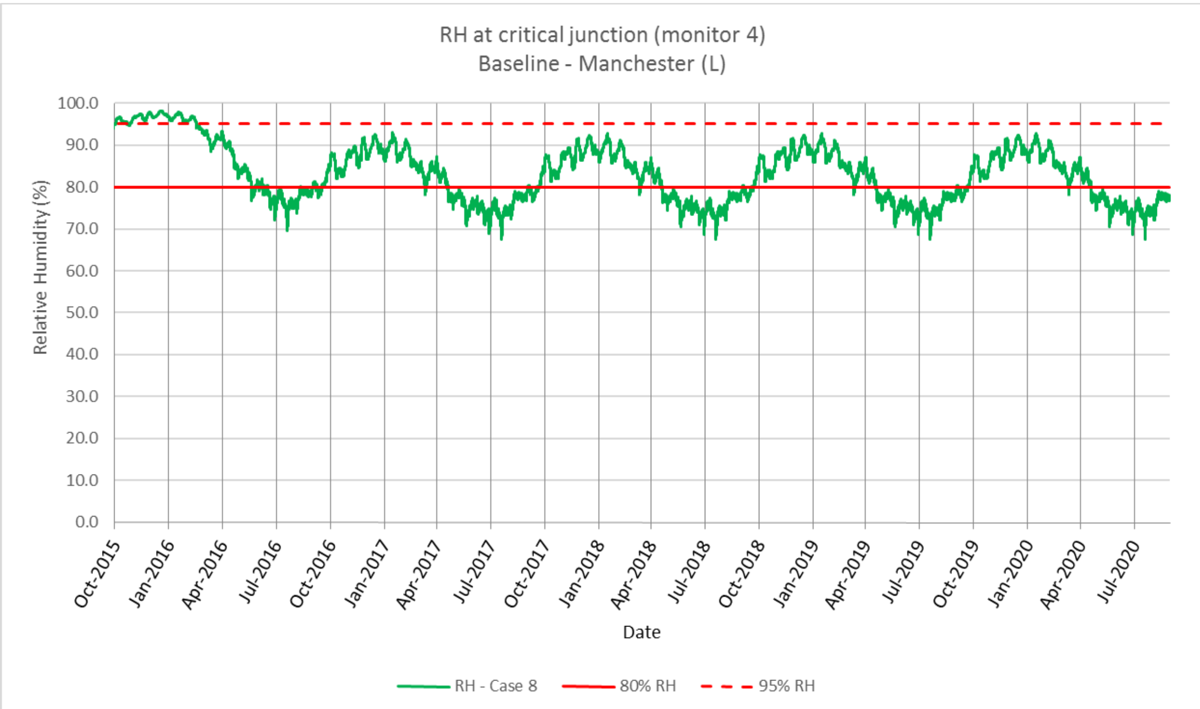


Figure 13: RH levels at monitored junction 4 for Case 8

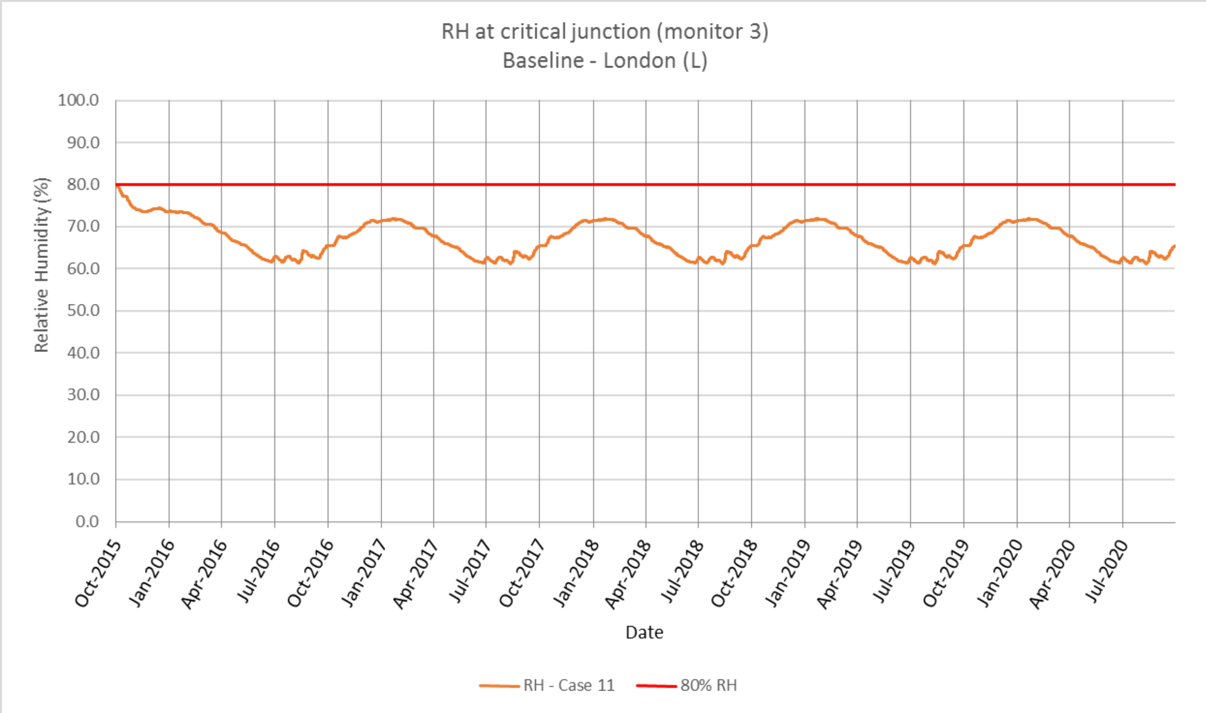


Figure 14: RH levels at monitored junction 3 for Case 11

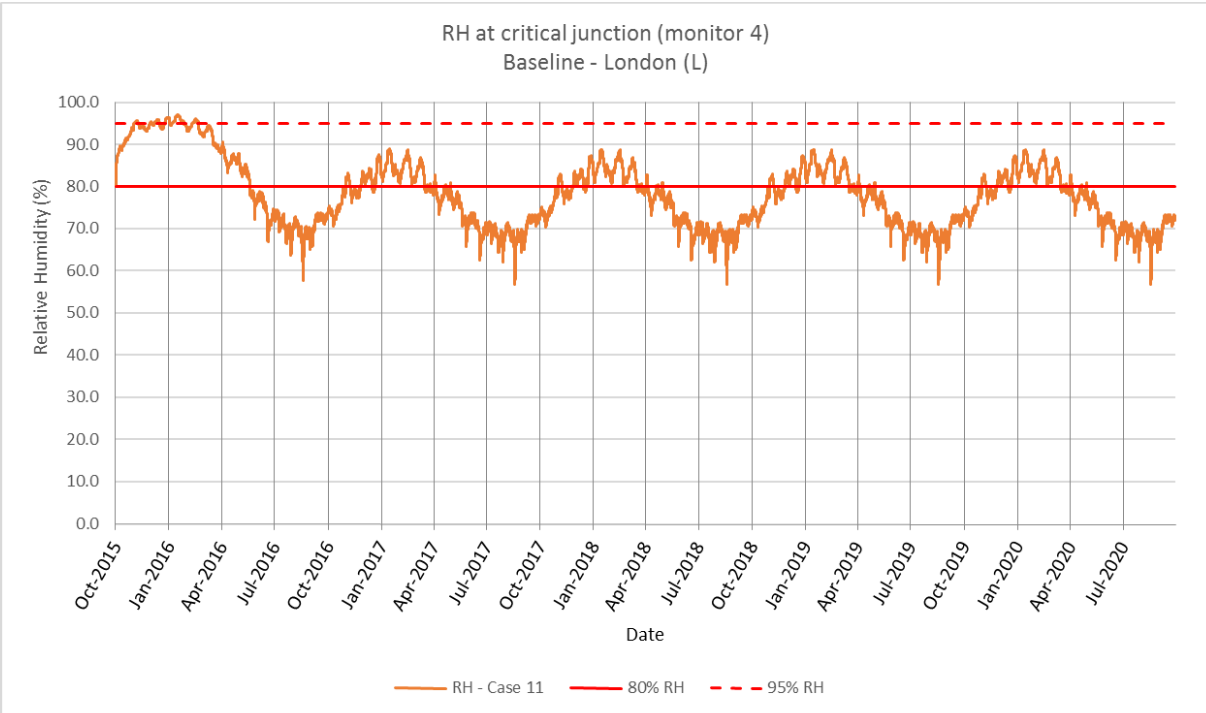


Figure 15: RH levels at monitored junction 4 for Case 11

8.3.4. Results Analysis

Moisture risk assessment criteria

All scenarios achieve equilibrium (which means that moisture does not accumulate over time). However, all scenarios display significantly different RH levels at the two different monitored junctions. The monitor 3 shows RH levels at the interface between the external chipboard layer and the foil layer being within the recommended 80% RH limit, while monitor 4 shows RH levels at the interface between the foil layer and the insulation layer being above the 80% RH limit for several months a year.

The moisture risk assessment criterion is normally set at an 80% RH upper limit. This level is retained for this analysis, as monitor 3 is an interface including a 'fragile' material and monitor 4 displays high RH levels, which could potentially reach the chipboard layer and create mould or moisture damage, where the foil layer on the insulation boards is not continuous (e.g. around edges).

Results

All scenarios are classed as 'risky'. Whilst they do not accumulate moisture over time and monitor 3 (interface external chipboard - foil) shows safe RH levels at or below 80%, monitor 4 (interface foil - insulation) shows RH levels above the 80% limit for all cases.

These results are summarised in the table below.

Table 7: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Risky	Case 5 Risky	Case 8 Risky	Case 11 Risky
Other	-	-	-	-

Effects of exposure zones

As the build-up is not exposed to the elements, the difference in exposure zone (due to different external weather conditions) only has a small effect on its hygrothermal performance.

These findings agree somewhat with the findings from the BS EN ISO 13788 (2012), in the fact that no interstitial condensation is occurring at the critical junction. However, the BS EN ISO 13788 (2012) calculation gives a false comfort, stating that the build-up is 'safe', when the WUFI modelling shows that, in all exposure zones, RH levels at the critical junction are kept close to the 80% RH threshold and could lead to moisture damage.

It is worth noting that the modelled build-up differs from the BS 5250 (2011) recommended build-up. Despite that the fact that the foil layer present on the warm side of the insulation can be considered equivalent (and technically more vapour resistant) to an AVCL layer, the recommended build-up in BS 5250 (2011) does not have a vapour retarder layer (such as a foil layer) present on the cold side of the insulation.

Some of the sensitivity analysis cases will include the modelling of the recommended BS 5250 (2011) build-up, to compare the prescriptive guidance to the results obtained through this modelling work.

8.3.5. 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 about 18% already reduces the load-bearing capacity of structural wood elements.

The graph below displays the moisture content in M-% in the external chipboard layer for the Case 2.

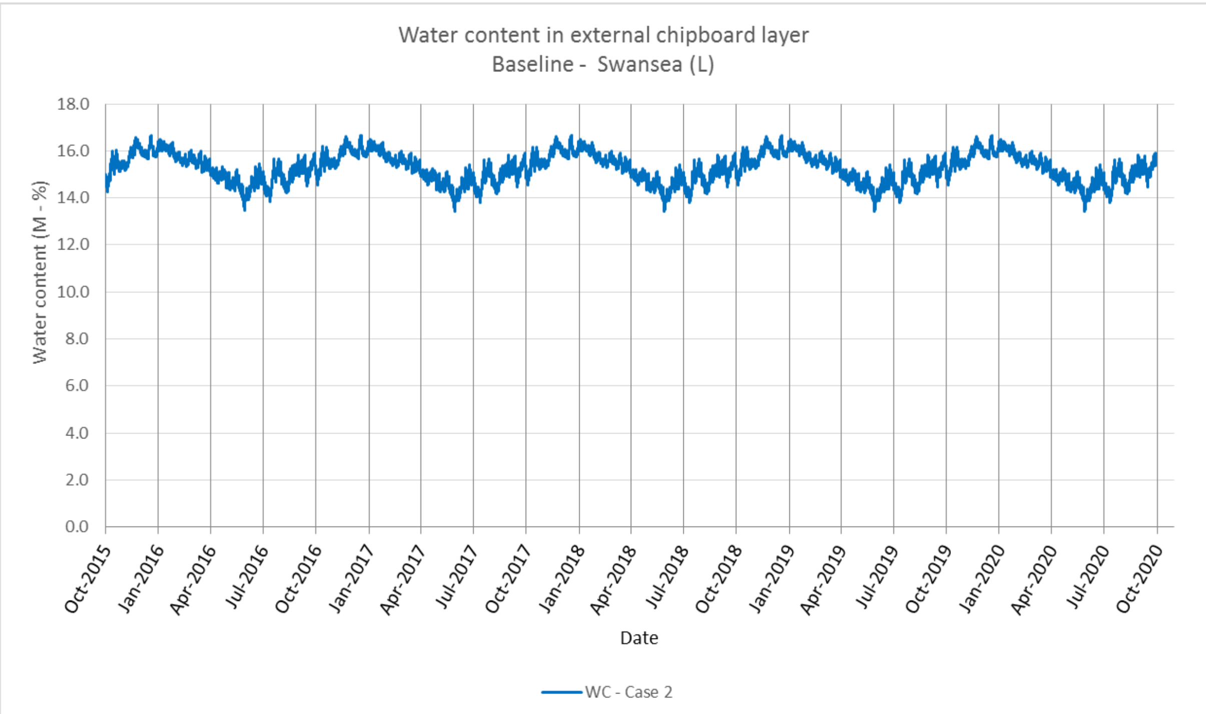


Figure 16: Moisture content in the timber soffit layer for Case 2

The graph shows that moisture levels in the external chipboard layer are considered 'safe'. These levels show the timber layer is not considered at risk of rotting or structural damage as they are kept below the 18 M-% threshold throughout the year.

It is worth noting that this external chipboard layer plays a structural role (supporting the insulation, the internal chipboard layer and the floor finish). This means that if this layer was to experience higher moisture content in the timber which could lead to rot or structural damages, this would have severe consequences on the build-up's performance.

8.3.6. Conclusions – Baseline

- Multiple monitors required to address issues related to 'exact' critical junction (as one interface corresponds to two junctions to be monitored) located adjacent to an insulation layer with foil layers
- Foil-backed insulation creating problems at the critical junction (technically between the foil layer and the insulation here, but likely to reach the fragile material layer at insulation board edges)
- Modelled build-up is different from the BS 5250 (2011) recommended build-up. However, the BS 5250 (2011) recommendation of the use of AVCL likely to be needed to improve hygrothermal performance of the build-up.

8.4. Sensitivity Analysis – Change in Material [Cases X.d]: Addition and removal of AVCL instead of foil layers

8.4.1. Baseline versus BS 5250 (2011) guidance and common practice

The baseline build-up differs slightly from the recommended build-up in BS 5250 (2011) section F.4.3. The recommended build-up includes closed-cell insulation without foil-paper facing and recommends an AVCL be installed between the insulation and the floor finish. Indeed, materials without foil facings such as EPS or XPS are often used for floor insulation (especially XPS for its high compressive strength and dimensional stability under load). The installation of an AVCL at this location is also not yet considered common practice in the industry.

Therefore, the following sensitivity analysis has been done:

- The first sensitivity analysis uses a build-up without any foil layers or AVCL
- The second sensitivity analysis uses a build-up with an AVCL (sd = 2m) installed between the insulation and the floor finish to match the BS 5250 (2011) recommended build-up, but still without foil layers

8.4.2. Sensitivity Analysis Cases

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the target Part L U-value (as per baseline cases):

Table 8: 4 sensitivity cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
Other				

8.4.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, between the cold side of the insulation and the external chipboard 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). Both sensitivity analysis cases (without and with AVCL) are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

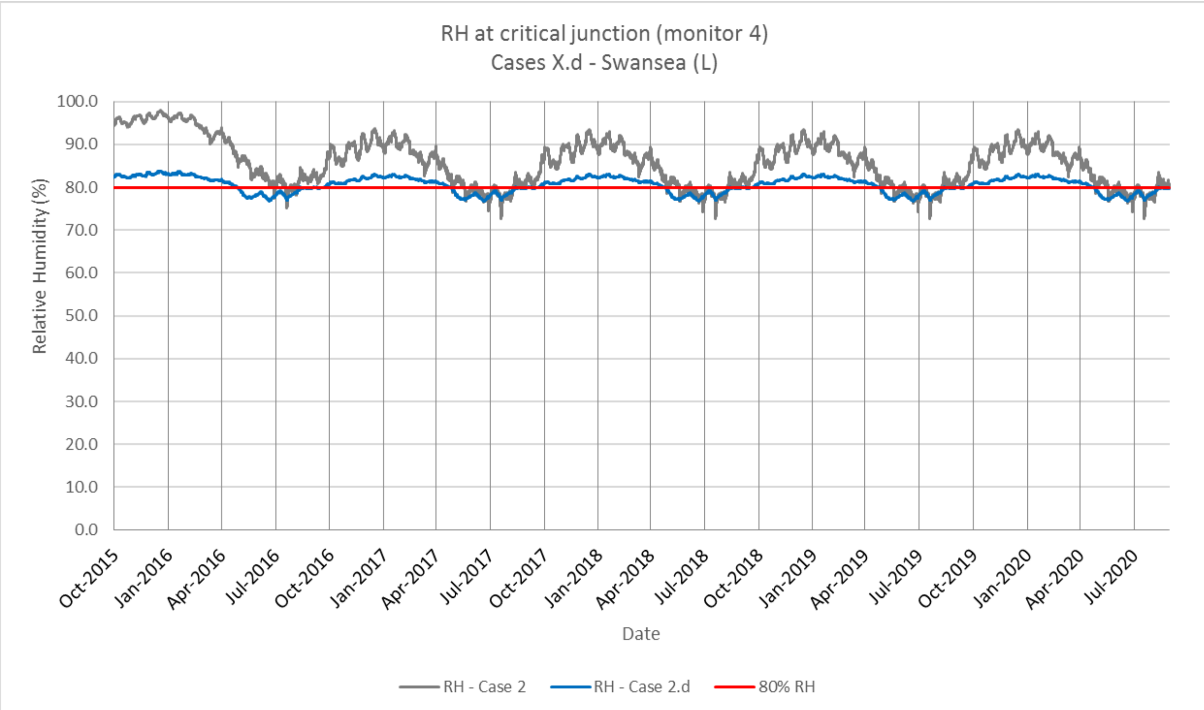


Figure 17: RH levels at critical junction for Cases 2 and 2.d (without AVCL or foil layers)

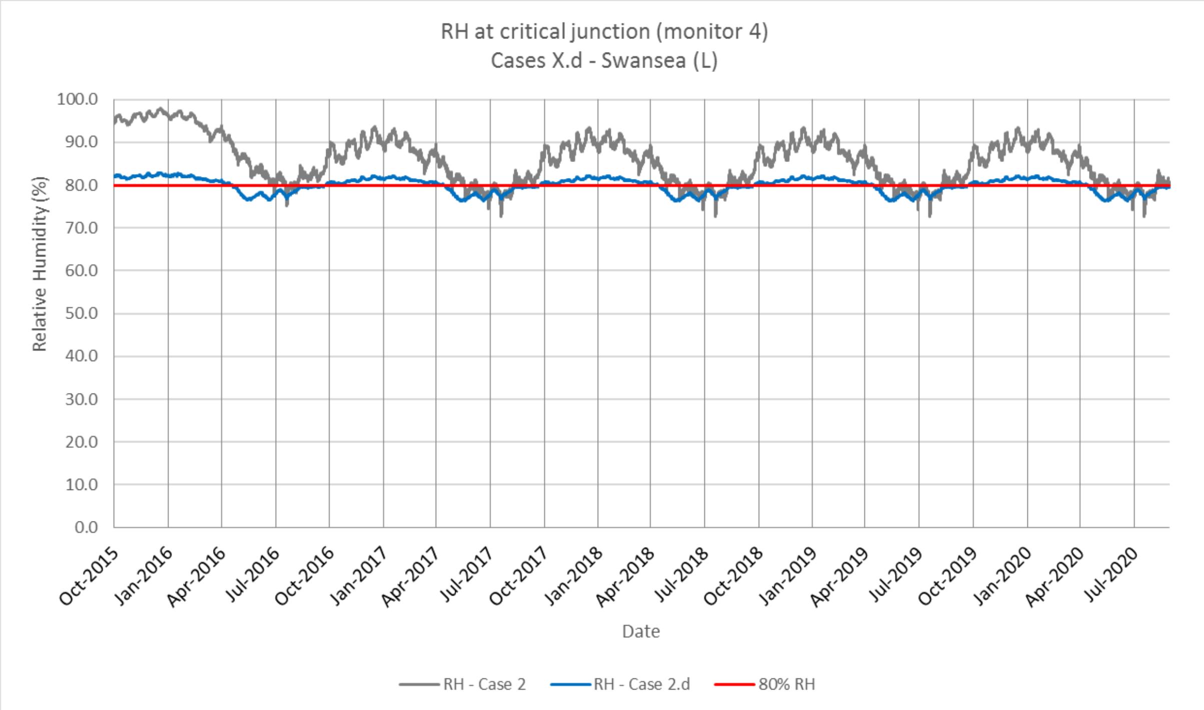


Figure 18: RH levels at critical junction for Cases 2 and 2.d (with AVCL)

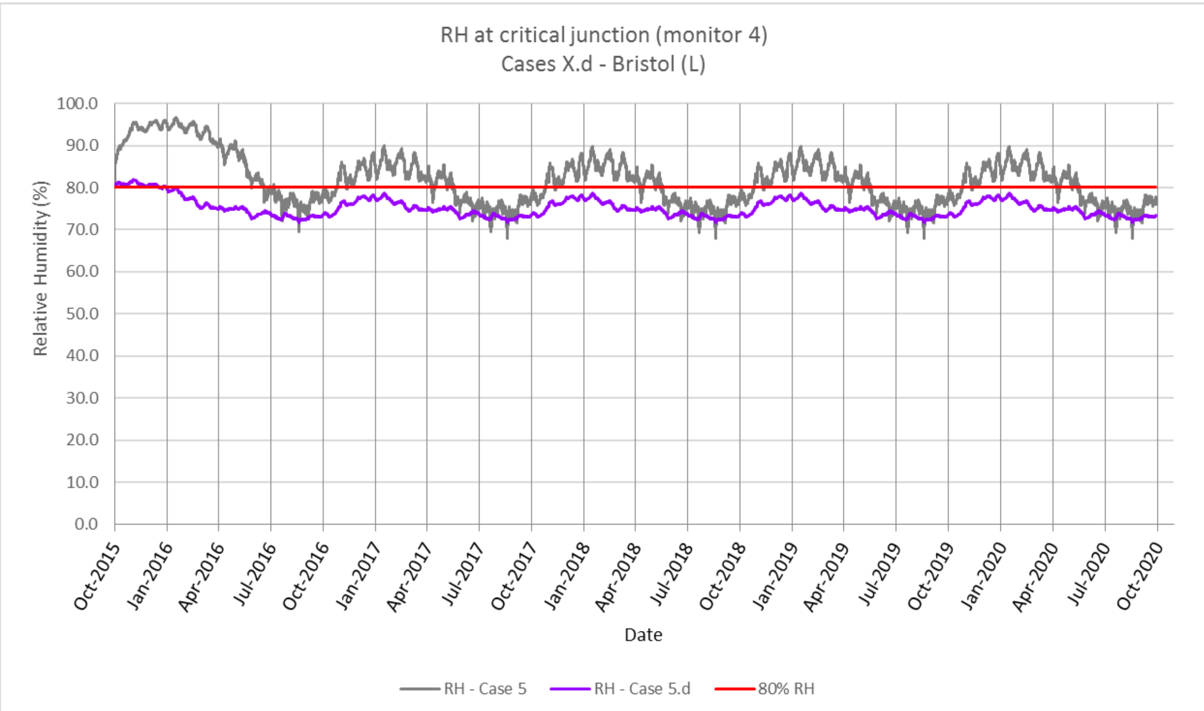


Figure 19: RH levels at critical junction for Cases 5 and 5.d (without AVCL or foil layers)

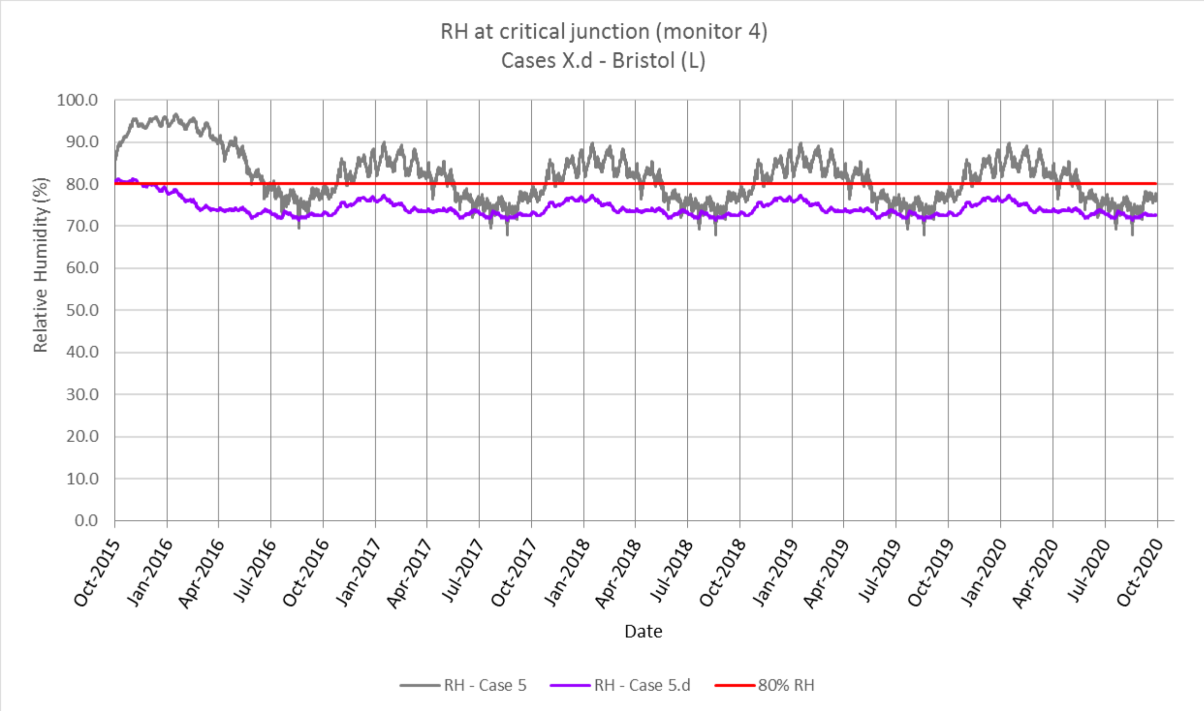


Figure 20: RH levels at critical junction for Cases 5 and 5.d (with AVCL)

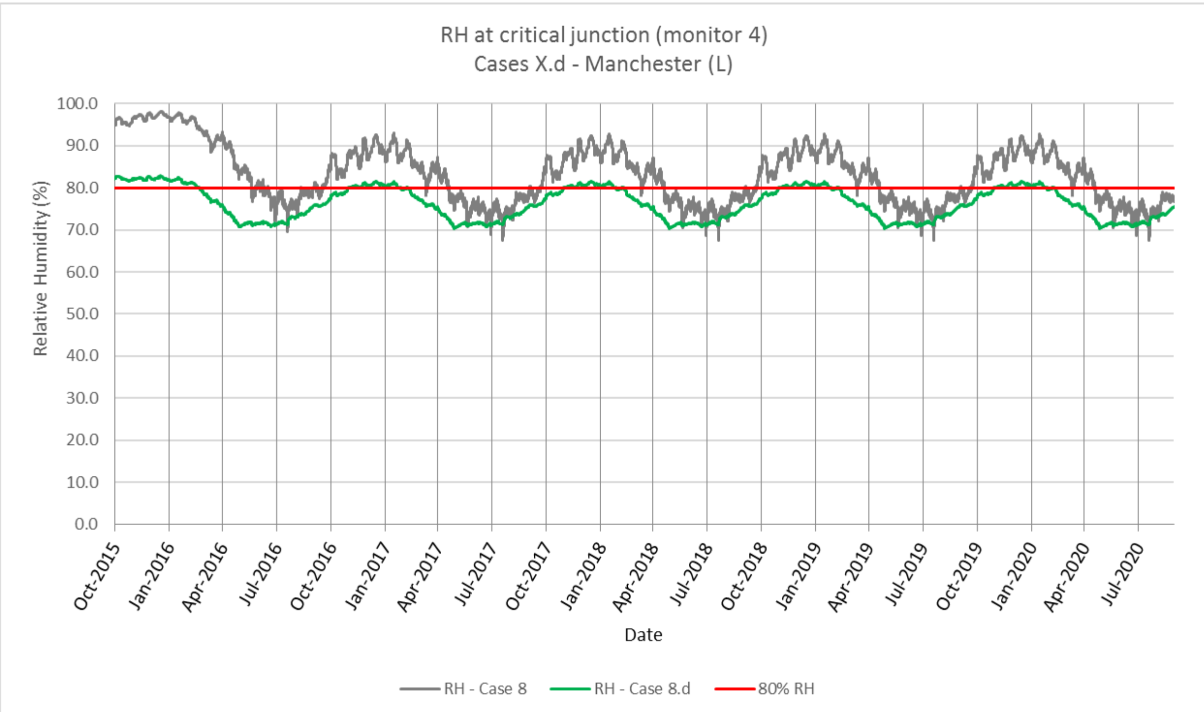


Figure 21: RH levels at critical junction for Cases 8 and 8.d (without AVCL or foil layers)

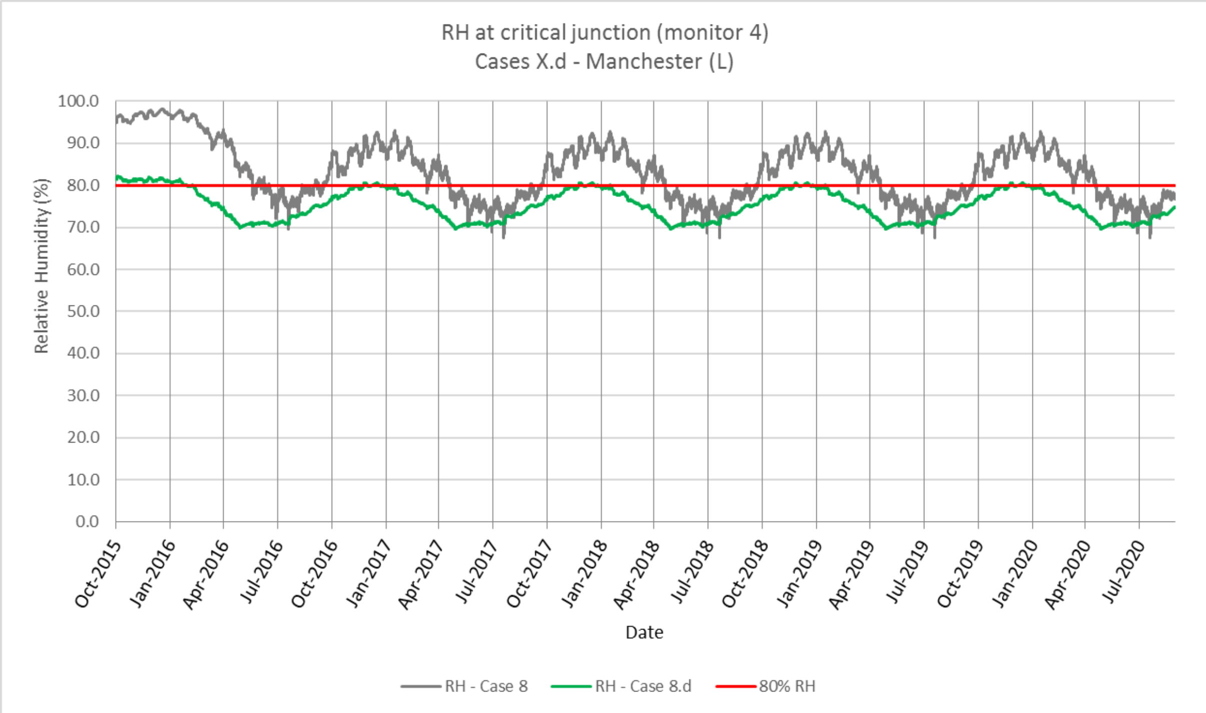


Figure 22: RH levels at critical junction for Cases 8 and 8.d (with AVCL)

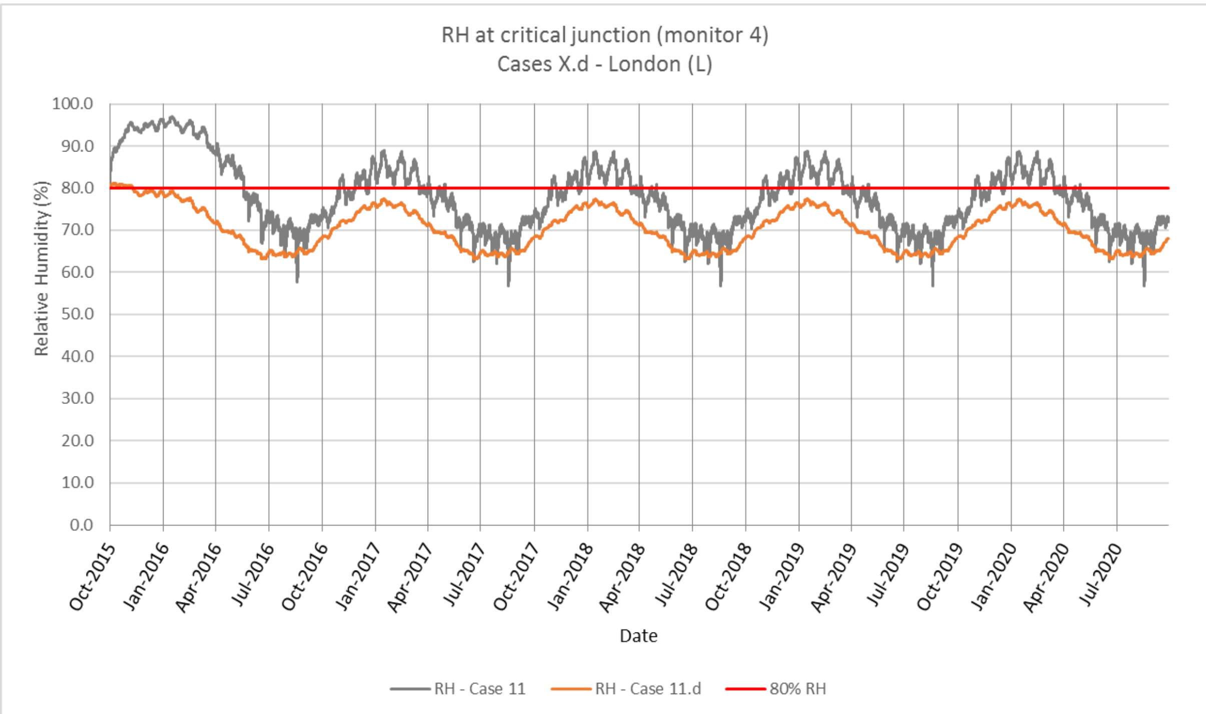


Figure 23: RH levels at critical junction for Cases 11 and 11.d (without AVCL or foil layers)

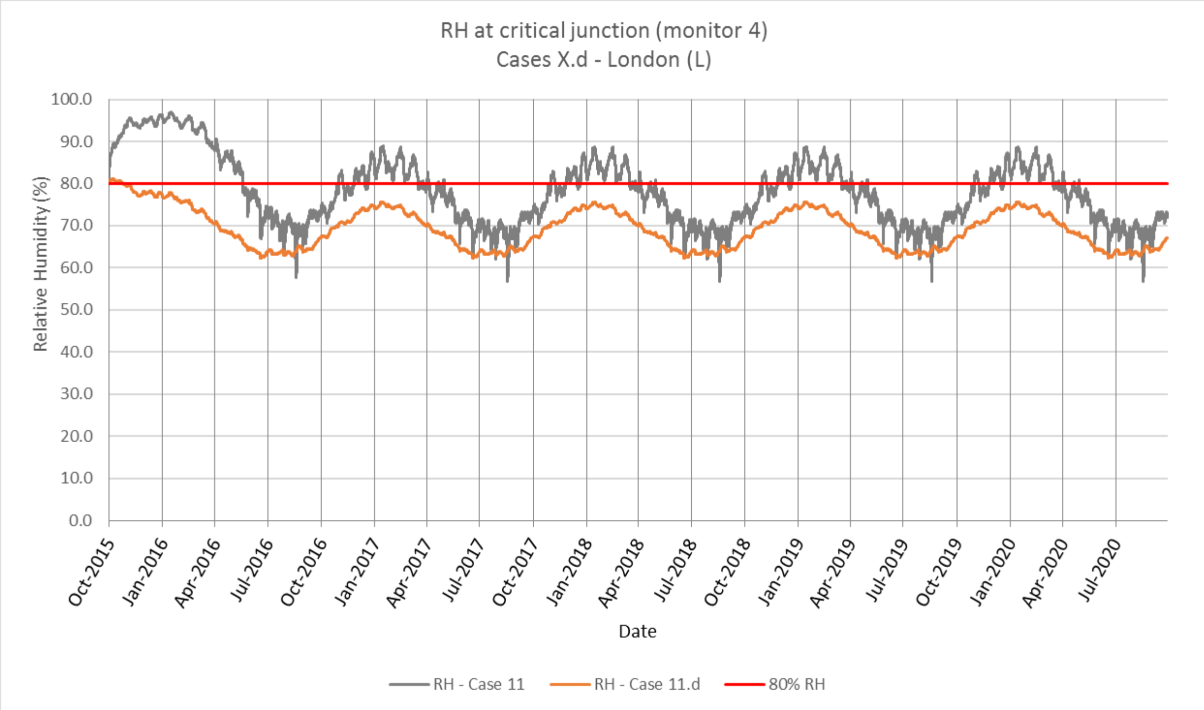


Figure 24: RH levels at critical junction for Cases 11 and 11.d (with AVCL)

8.4.4. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The graphs show that all cases modelled in this sensitivity analysis perform better than their respective baseline cases, particularly in the winter, as the RH profiles in the sensitivity analysis are consistently kept lower than RH levels in the baseline cases. This is due to the removal of the highly vapour resistant foil layers which allows for better moisture movement and avoids moisture staying trapped in certain locations.

This improvement in hygrothermal performance is significant, as RH levels at equilibrium are consistently maintained below the 80% RH threshold in all cases apart from Swansea (zone 4). This means that all cases, apart from Swansea, are considered a ‘pass’ in accordance with the moisture risk assessment criteria. As RH levels are kept above the 80% threshold for long periods of time (longer than a month), this case is the only case in this sensitivity modelling that is considered as ‘fail’.

Results

The table below summarises the performance of both sensitivity analysis cases (without and with AVCL):

Table 9: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2.d Fail	Case 5.d Pass	Case 8.d Pass	Case 11.d Pass
Other	-	-	-	-

Effects of exposure zones

Whilst the build-up is not exposed to the elements, there is some difference in performance related to exposure zones as the higher external RH conditions in the Swansea climate have an impact on the hygrothermal performance of the build-up. This variation is significant enough to cause the build-up to fail according to the moisture risk assessment criteria.

Presence of AVCL

The sensitivity analysis results seem to show that the AVCL layer does not have an impact on the hygrothermal performance of the build-up, as RH levels at the critical junction are very similar independently to the presence or absence of the AVCL.

It is important to note that the build-up modelled in WUFI is done in theoretical conditions, which means that all modelled layers are assumed to be continuous. However, in reality, insulation layers are unlikely to be fully continuous, leading to gaps in the insulation layer (where infiltration could take place and lead to interstitial condensation). As such, despite these results indicating it has little benefit, the presence of a dedicated continuous taped AVCL sheet material is important to prevent moisture-laden air making its way through the gaps in the insulation layer, particularly by convection, and condensing when it reaches its dew point or causing high RH within the build-up. Therefore, particular care should be given to ensuring good airtightness in this build-up by maintaining the inclusion of an AVCL.

Continuity of Foil Layers

It is worth noting that the sensitivity analysis results are compared to the results of the ‘worst’ critical junction in the baseline cases (as two critical junctions were monitored). The ‘worst’ critical junction was located between the cold side of the insulation and the external foil layer (due to the foil layer trapping moisture travelling through the build-up). The additional monitored junction was located between the external foil layer and the external chipboard layer, displaying lower RH levels due to the protection of the junction by the foil layer.

As discussed in the baseline results analysis section, if the complete continuity of the foil layers present on both sides cannot be ensured, these high RH levels present at the critical junction will keep travelling through the build-up where the foil layer is not continuous. These sensitivity analysis cases show that, if this build-up is used in conditions where it will not be feasible to ensure the continuity of these foil layers, then it is safer to use an insulation material without foil-paper facings (and with a continuous AVCL) to protect the critical junction as much as possible.

8.5. Conclusions

- The results are also in accordance with calculations done following the BS EN ISO 13788 (2012) method, which demonstrates no interstitial condensation risk in this build-up. But these results are not fully in agreement, as the BS EN ISO 13788 (2012) calculations declare the build-up ‘safe’, while WUFI modelling shows that the build-up is considered ‘risky’ due to high RH levels at the critical junction, where ‘fragile’ material is present
- Timber considered not at risk, in terms of total moisture content, if floor void is well ventilated
- However, build-up is ‘risky’ in some climates, according to the moisture risk assessment criteria, as mould could grow on the timber surface (‘safer’ when presence of continuous AVCL layer above the insulation).
- Removal of foil layers and replacement with a continuous AVCL = measures to make the build-up safer (i.e. agreement with BS 5250 (2011) recommendations)

Notes:
Critically, this layer is discontinuous with gaps between insulation boards.
Also, whilst polyurethane has been modelled here, more moisture sensitive insulation boards may be used.

9. Typology R2: In-situ ground bearing concrete floors (uninsulated) Retrofit Measure: insulation above

The R2 typology is ground bearing concrete slab prior to retrofit. The retrofit measure is to install insulation above the slab.

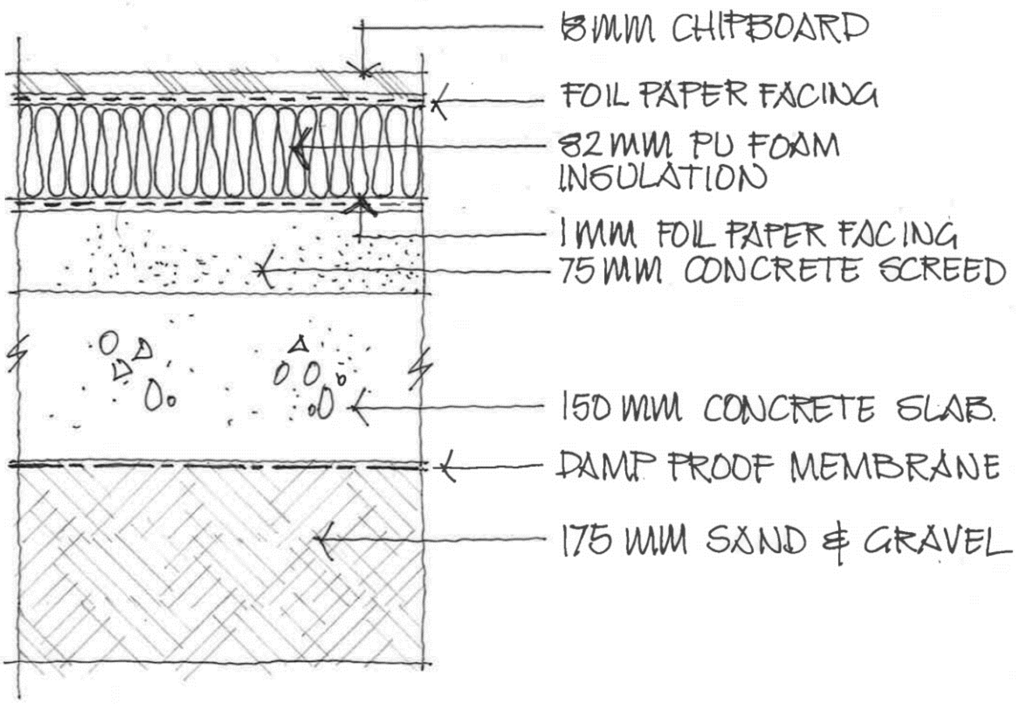


Figure 25: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

9.1. Assessment Method

No element of this construction type is exposed to either wind-driven rain or solar gains. This build-up is often also protected from rising damp with the presence of the damp-proof membrane (DPM) layer below the slab, and subject to relatively constant external conditions (being in direct contact with the ground). Under these conditions, moisture transfer is mainly driven by vapour diffusion. Therefore, the build-up should not require dynamic simulation following BS EN 15026 (2007).

Since the BS EN ISO 13788 (2012) method has some limitations, such as not accounting for moisture storage within elements, this method should be used with some caution for accurate moisture risk assessment of solid ground bearing floors (as mentioned on the calculation document itself).

The results from the Glaser method analysis show that the post-retrofit build-up is not considered being a ‘safe’ build-up, with persistent interstitial condensation occurring throughout the year at the interface between the existing screed and the retrofitted insulation.

Prescriptive guidance BS 5250 (2011) (paragraph F.3) states the following: *'If thermal insulation is installed above the floor slab, there is a risk of interstitial condensation occurring on the upper surface of the floor slab. To prevent that, an AVCL with a vapour resistance equivalent to that of the DPM should be laid over the thermal insulation'*.

It is worth nothing that this recommendation might not be directly applicable to a retrofit situation, as the status of any existing DPM would be unknown, in terms of a DPM being present or not in the build-up, and if so, what moisture resistance characteristics it has.

9.2. Build-up

Please find below the build-up of the typology.

9.2.1. Build-up (pre-retrofit)

Build-Up:

- 75mm concrete screed
- 150mm concrete slab
- 1mm DPM (sd = 136m)
- 175mm sand and gravel

9.2.2. Build-up (post-retrofit)

Build-Up:

- 18mm chipboard
- 1mm foil paper facing (sd = 14m)
- 82mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 75mm concrete screed
- 150mm concrete slab
- 1mm DPM (sd = 136m)
- 175mm sand and gravel

9.3. Connective Effects

9.3.1. Junction Modelling

The guidance in BS 5250 (2011) (paragraph F.3), identifies an additional risk of surface condensation: *'On ground bearing floors, there is a risk of surface condensation forming, particularly at the junction with external walls and at external corners. That risk may be eliminated by providing adequate heating and ventilation of the occupied space. In order to avoid thermal bridging, thermal insulation should be provided to the edges of the slab build-up'*.

As connective effects (leading to the risk of mould growth) around junctions play a significant role with this typology, thermal bridging analysis using THERM was undertaken of a post-retrofit R2 floor build-up adjoining a typical uninsulated solid wall.

The model assesses the impact of retrofit floor insulation at the corner internal surface temperature (with the risk of mould growth in this junction), as well as at the junction between the existing screed and the newly installed floor insulation.

9.4. Results

9.4.1. Junction Modelling

Figure 26 illustrates the junction between an R2 floor type and an uninsulated solid wall.

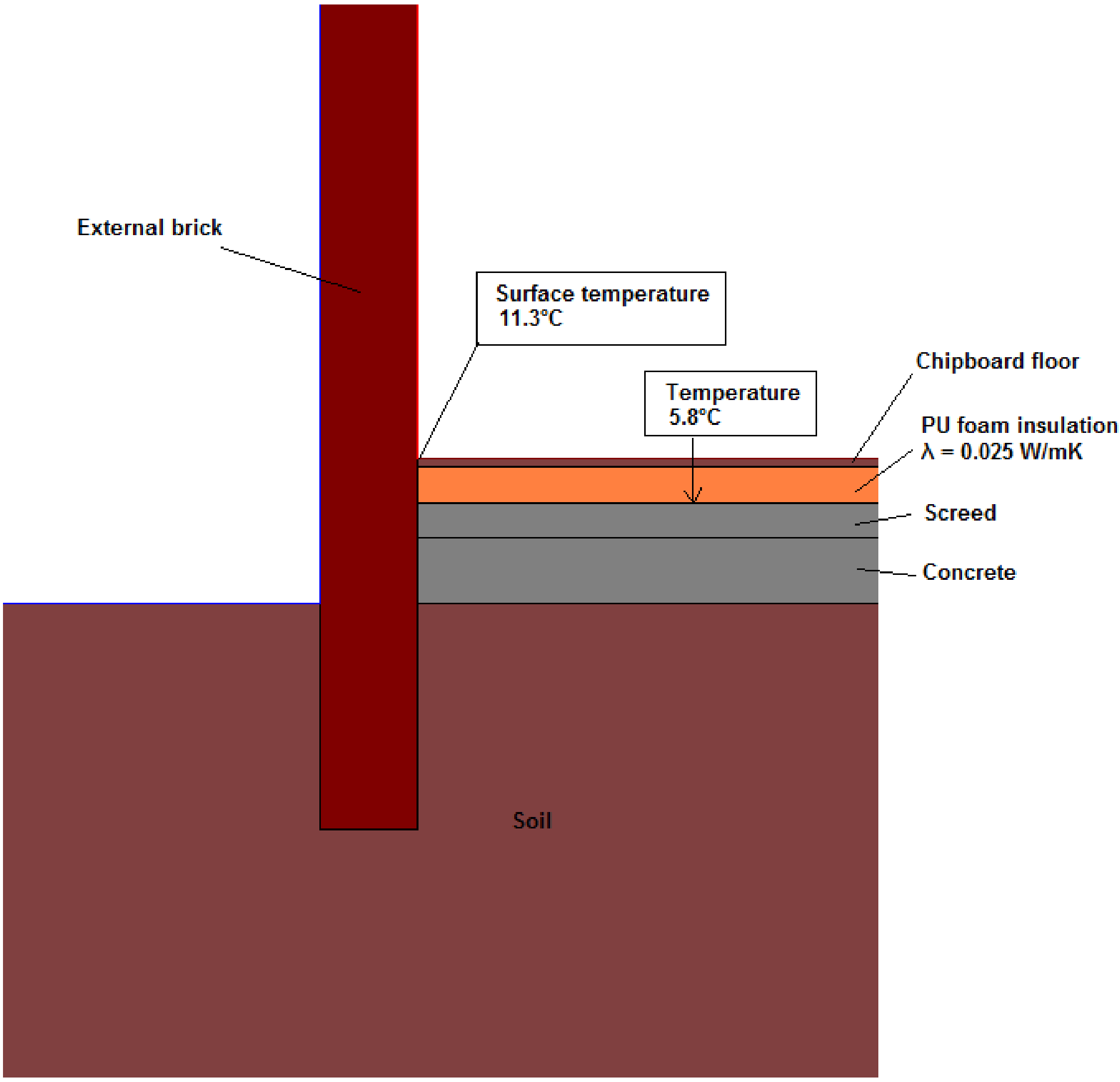


Figure 26: Junction between floor type R2 and an uninsulated solid wall

The lowest corner internal surface temperature (T_{si}) is 11.3°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.54, which indicates a significant risk of condensation and mould growth conditions at this junction, as f_{Rsi} is below 0.75.

The temperature at the junction of the screed and the newly installed insulation is indicated to be 5.8ºC. It is worth noting that this is a sufficiently cold temperature for interstitial condensation to occur at that junction if the other conditions are adequate (presence of air and moisture travelling through the build-up, driven by the difference in vapour pressures).

9.4.2. Conclusions

With the modelled conditions using a 20°C internal temperature (T_i) and 0°C external temperature (T_e), all surface temperatures (T_{si}) should have a minimum temperature of 15°C to avoid mould risk to meet the f_{Rsi} criteria. As the junction modelled in Figure 26 does not meet this criteria, displaying a corner internal surface temperature T_{si} of 11.3°C, the junction is at significant risk of mould growth.

10. Typology R4: Beam and block ground floors Retrofit Measure: Insulation added above

The R4 typology is an uninsulated concrete beam and block floor prior to retrofit. The retrofit measure is to install PU foam insulation and chipboard flooring above the screed.

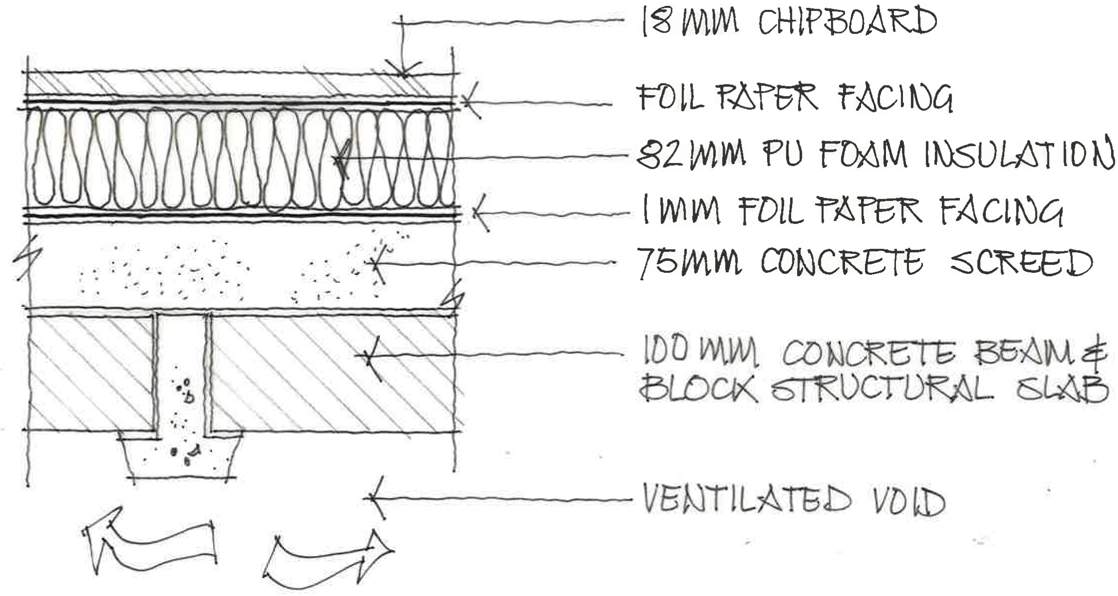


Figure 27: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

10.1. Assessment Method

As the concrete beam and block layer is partially exposed (the underside is exposed to external temperatures and RH levels due to the ventilated subfloor, but without wind-driven rain or solar gains), the movement of moisture in this layer is driven by vapour diffusion. This mechanism is dealt with in the BS EN ISO 13788 (2012) calculation method, and therefore this method should be able to provide an accurate assessment of the hygrothermal performance of this build-up.

The results from the Glaser method analysis show that this build-up is generally considered to be a ‘safe’ build-up. The calculation shows that interstitial condensation occurs during the winter season, but evaporates completely during the summer months.

It is common for surface condensation to occur in the pre-retrofit case. This can be simply explained by the lack of insulation leading to a floor surface temperature not high enough to be above the dew point.

The results regarding the lack of interstitial condensation accumulating over the years will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

10.2. Build-up

10.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 75mm sand cement concrete screed
- 100mm concrete beam & block

The DPM layer has been excluded in the baseline build-up, as the presence of this layer is not considered typical in existing older construction.

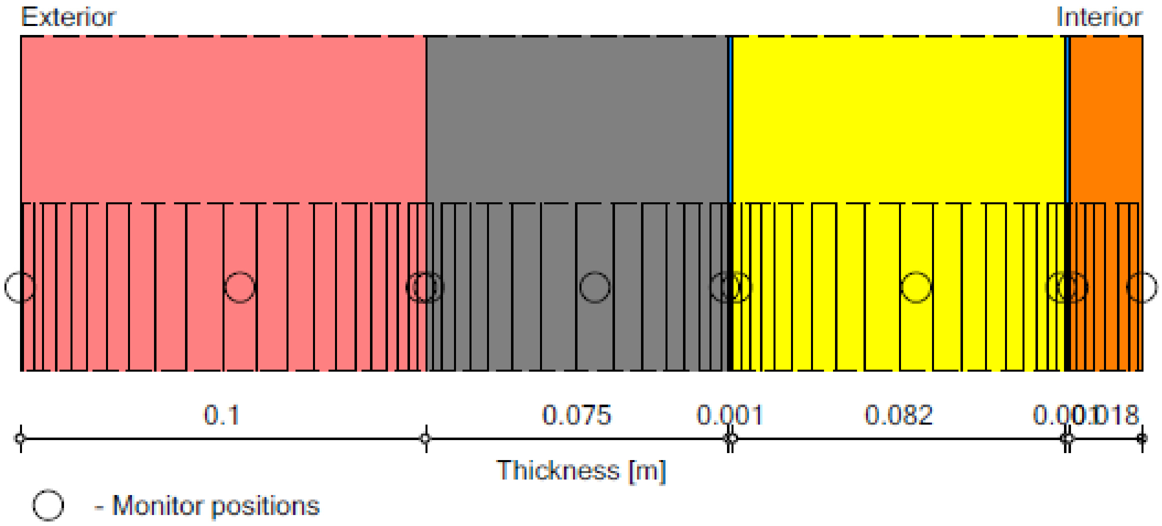
10.2.2. Initial Conditions

Although the materials present in the pre-retrofit build-up are not exposed to wind-driven rain, the concrete blocks and screed are heavy weight materials, 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)

Build-Up:

- 18mm chipboard
- 1mm foil paper facing (sd = 14m)
- 82mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 75mm sand cement concrete screed
- 100mm concrete beam & block



Materials:

	- Concrete Blocks, pumice aggregate	0.1 m
	- Concrete Screed, mid layer	0.075 m
	- *Foil paper facing (sd = 14m) (unlocked)	0.001 m
	- *PU (heat cond.: 0,025 W/mK)	0.082 m
	- *Foil paper facing (sd = 14m) (unlocked)	0.001 m
	- *Chipboard	0.018 m

In many cases, such a deep thickness of retrofit insulation may be impractical to install, since the interaction between the raised floor level and doors (as well as around stairs) may result in conflicting requirements. The analysis of floor type N4 shows that moisture risk increases as insulation levels increase. Therefore, the thickest layer of insulation to be retrofitted will be tested here, despite its installation being unrealistic in practice.

WUFI Input Parameters

As the crawl space is considered ventilated, the reinforced concrete beams 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 floor blocks) is exposed to different external conditions due to the crawl space acting as a protective layer against wind-driven rain.

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
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)

10.3. Baseline Results

10.3.1. Baseline Cases

The 8 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 10: 4 baseline cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

10.3.2. Critical Junction

For this typology, the focus is on the RH levels at the interface of the cold screed and the insulation. Since an AVCL / vapour retarder (in the form of a foil layer) is located between the screed and the retrofitted insulation, the interface to be monitored is actually composed of two monitors (similarly to the R1.2 typology):

- Actual interface between the concrete screed and the external foil layer present on the insulation layer (listed as monitor 6 here)
- Interface between the external foil layer and the insulation (listed as monitor 7 here)

Similarly to the R1.2 typology, the build-up is protected from wind-driven rain and moisture is driven by vapour diffusion. Consequently, due to the high vapour resistance of the external foil layer, RH levels are lower / safer below this layer (i.e. at the monitor 6 location). Therefore, RH levels at monitor 7 only will be displayed in this report, as monitor 7 has the highest / most risky RH levels out of the two monitors.

This critical junction is correctly identified in the BS EN ISO 13788 (2012) assessment, but the presence of interstitial condensation in this calculation is not associated with the failing of the build-up, as the calculation shows that the interstitial condensation occurring at the critical junction evaporates during the summer.

10.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, at monitor 7, i.e. on the cold side of the insulation layer between the external foil layer and the insulation itself.

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).

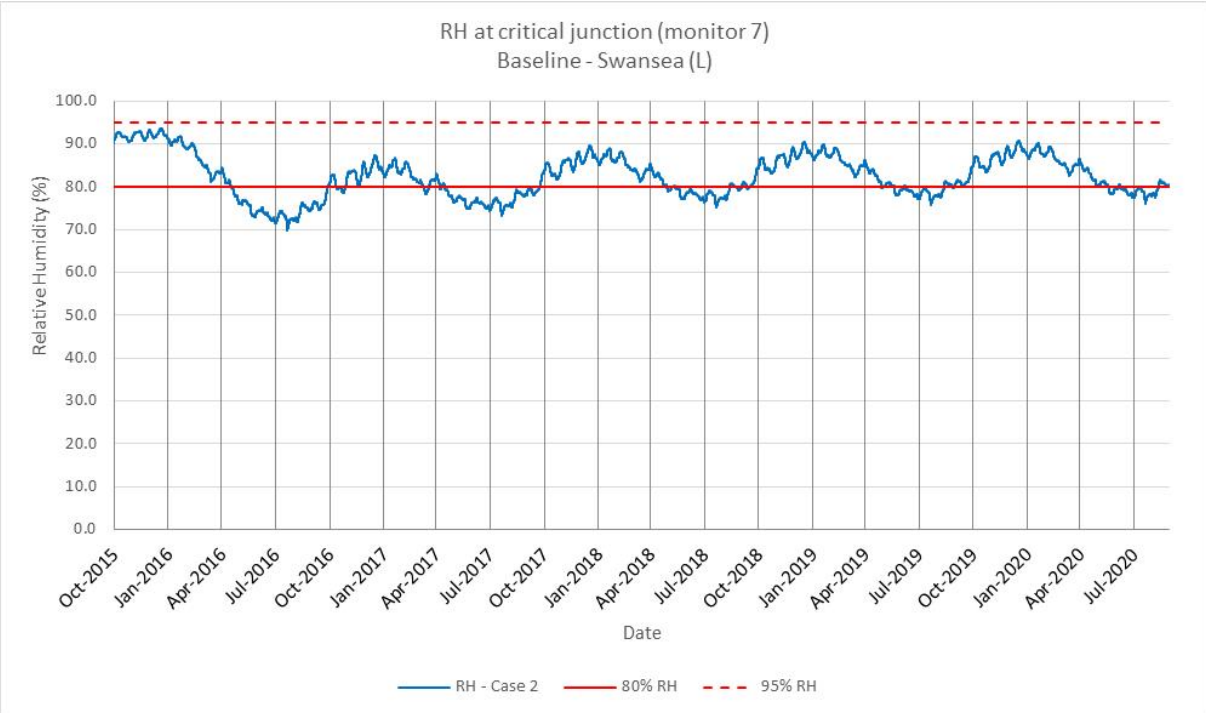


Figure 28: RH levels at critical junction for Case 2

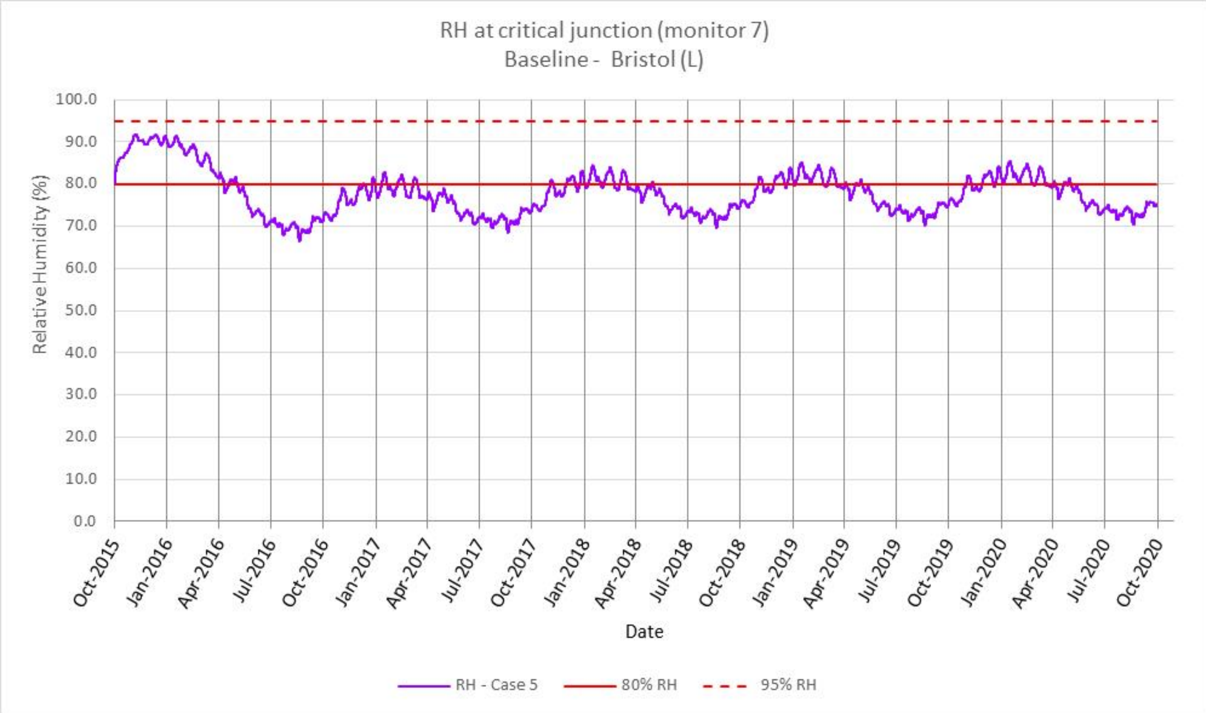


Figure 29: RH levels at critical junction for Case 5

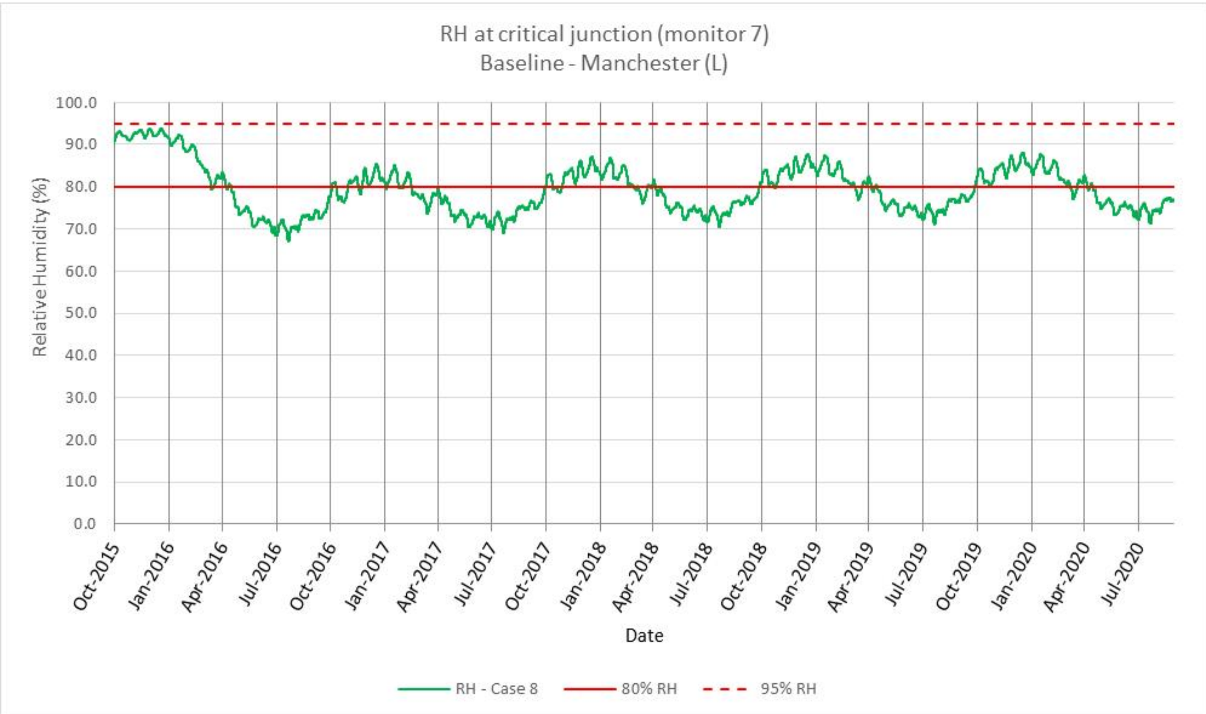


Figure 30: RH levels at critical junction for Case 8

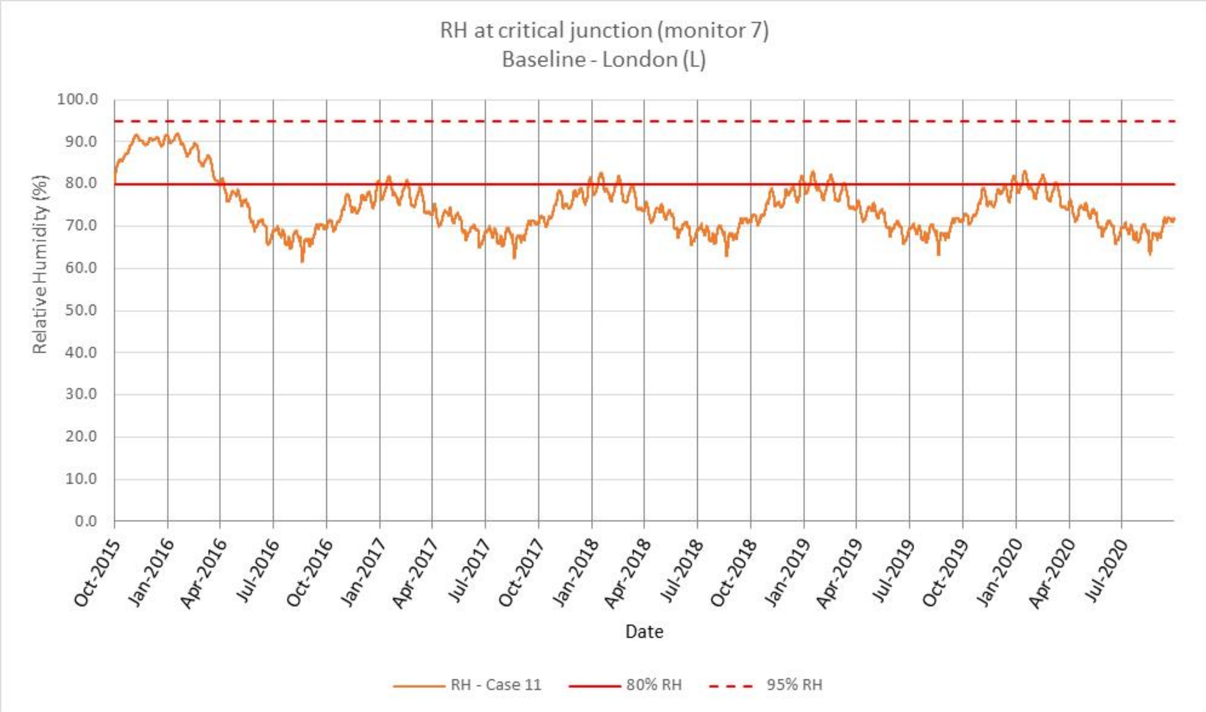


Figure 31: RH levels at critical junction for Case 11

10.3.4. Results Analysis

Moisture risk assessment criteria

All cases do not quite achieve complete equilibrium during the 5-year timeframe. These cases were run for a longer modelling period and showed that equilibrium was reached between year 6 and year 7.

The moisture risk assessment criteria is normally set at 80% for the upper RH limit. However, this criteria can be relaxed here from 80% to 95% for this build-up at this monitored interface, as there is no significant food for mould growth, little to no air is (theoretically) in the build-up and RH peaks happen during winter (please refer to explanation in typology N19 in *Using numerical simulation to assess moisture risk in new constructions* report for further details).

All retrofitted cases display RH levels drying from the uninsulated state towards equilibrium, always staying below the 95% threshold. According to the moisture risk assessment criteria, these cases are therefore considered a ‘pass’.

Following the relaxation of the RH threshold from 80% to 95%, these results agree with the BS EN ISO 13788 (2012) calculations as both methods declare the build-up safe. However, it is worth noting that the BS EN ISO 13788 (2012) calculation shows that interstitial condensation occurs at the critical junction during winter months, which is different from what the WUFI modelling shows (as per the baseline graphs, higher RH levels occur in winter, but they do not go above 90% when at reaching equilibrium, meaning that interstitial condensation does not occur).

Results

These results are summarised in the table below.

Table 11: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
Other	-	-	-	-

Effects of exposure zones

As the build-up is not directly exposed to the elements, there is a very limited impact of different climatic conditions, meaning the hygrothermal performance of the build-up in different exposure zones is very similar. The difference in RH levels can be explained by the difference in external conditions (temperature and RH levels) in the four exposure zones. Therefore, any sensitivity analysis will be performed for one exposure zone only (Zone 4 – Swansea).

10.3.5. Conclusions – Baseline

These findings from WUFI modelling are similar to the findings from the BS EN ISO 13788 (2012) assessment, declaring the build-up safe while still highlighting the critical junction at risk of interstitial condensation. However, the two assessment methods differ, with the BS EN ISO 13788 (2012) stating the presence of interstitial condensation in winter (with full evaporation in summer) while the WUFI modelling following BS EN 15026 (2007) shows no interstitial condensation, as RH levels do not go higher than 90% at equilibrium.

10.4. Sensitivity Analysis – Extended time – 10 years

As neither the Swansea, Bristol nor Manchester cases achieve complete equilibrium, the first sensitivity analysis is to rerun the Zone 4 - Swansea case (case 2) for an extended period of 10 years.

10.4.1. Graphs at Critical Junction

The graph displayed below shows the RH levels at the critical junction (which is the same as in the baseline cases), on the cold side of the insulation layer, between the external foil layer and the insulation itself, for the Swansea baseline case for an extended modelling period of 10 years.

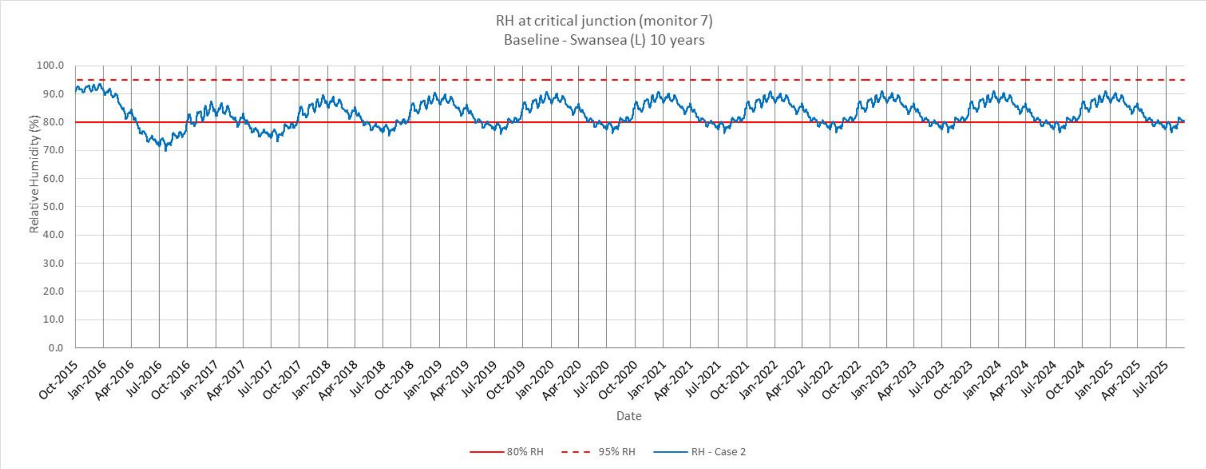


Figure 32: RH levels at critical junction for Case 2

10.4.2. Conclusions – Sensitivity Analysis Cases – 10 years

The results confirm that equilibrium is reached during year 6 to year 7 of the modelling period which means that the 5-year modelling period used in this typology is providing results that are close enough to equilibrium to assess qualitatively the hygrothermal performance of each case. Therefore, the conclusions for the baseline cases are retained.

10.5. Sensitivity Analysis – Change in Material [Case X.d]: Addition of a DPM in the pre-retrofit build-up

Presence of DPM in pre-retrofit floor

Although a DPM within the structure of an existing beam and block floor is unlikely to be present, it is possible that a DPM may have been installed above the block construction below the screed. This may happen in cases where the DPM is also serving as e.g. a Radon barrier. Since a DPM in this position is likely to have some impact on the hygrothermal performance of the build-up, it is useful to conduct a sensitivity analysis on this variation.

10.5.1. Sensitivity Analysis Cases

The cases are set across the Zone 4 wind-driven rain exposure zone, meeting the target Part L U-value (as per baseline cases):

Table 12: 4 sensitivity analysis cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1.d	Case 4.d	Case 7.d	Case 10.d
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
Other	-	-	-	-

10.5.2. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases) for the sensitivity analysis cases, with the critical junction being on the cold side of the insulation layer, between the external foil layer and the insulation itself.

The sensitivity analysis cases (with the existing DPM layer below the screed) are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

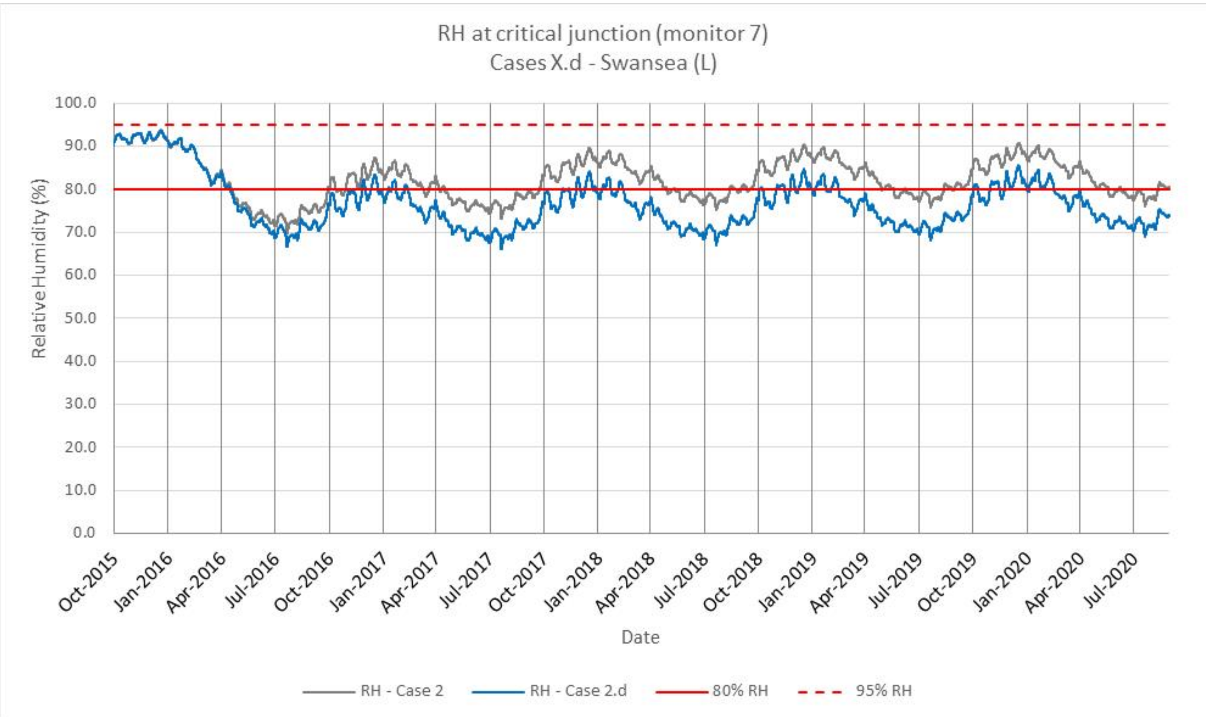


Figure 33: RH levels at critical junction for Cases 2 and 2.d

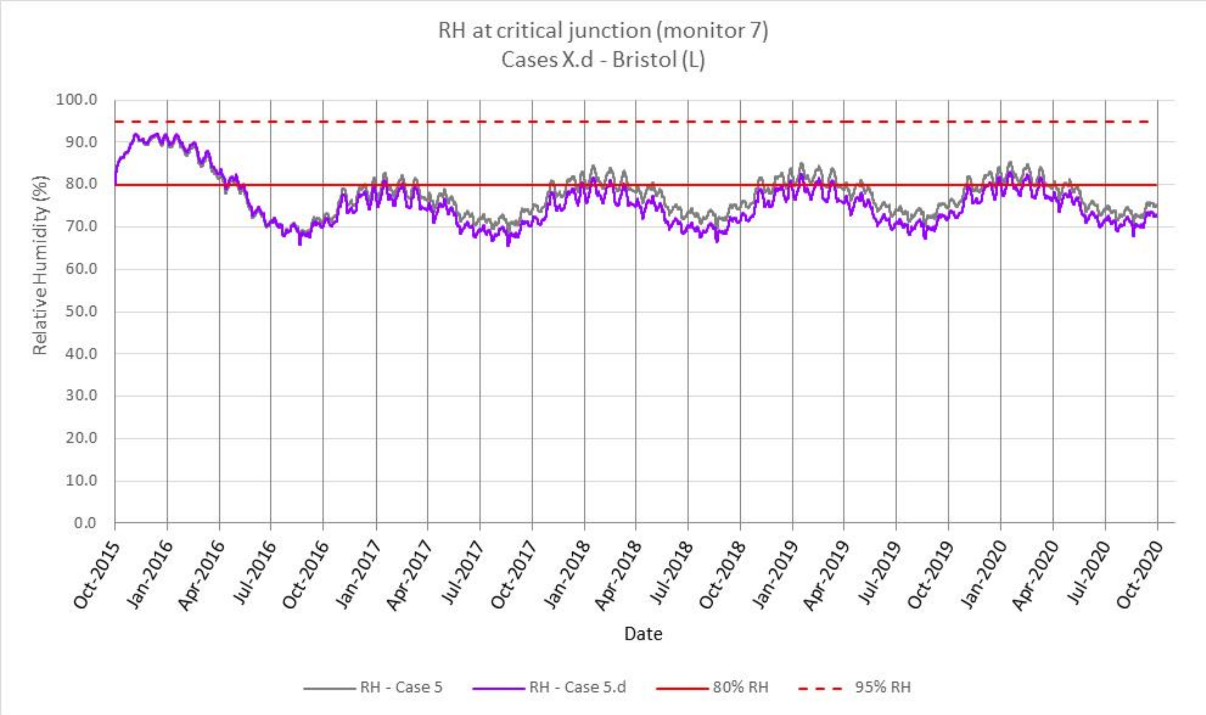


Figure 34: RH levels at critical junction for Cases 5 and 5.d

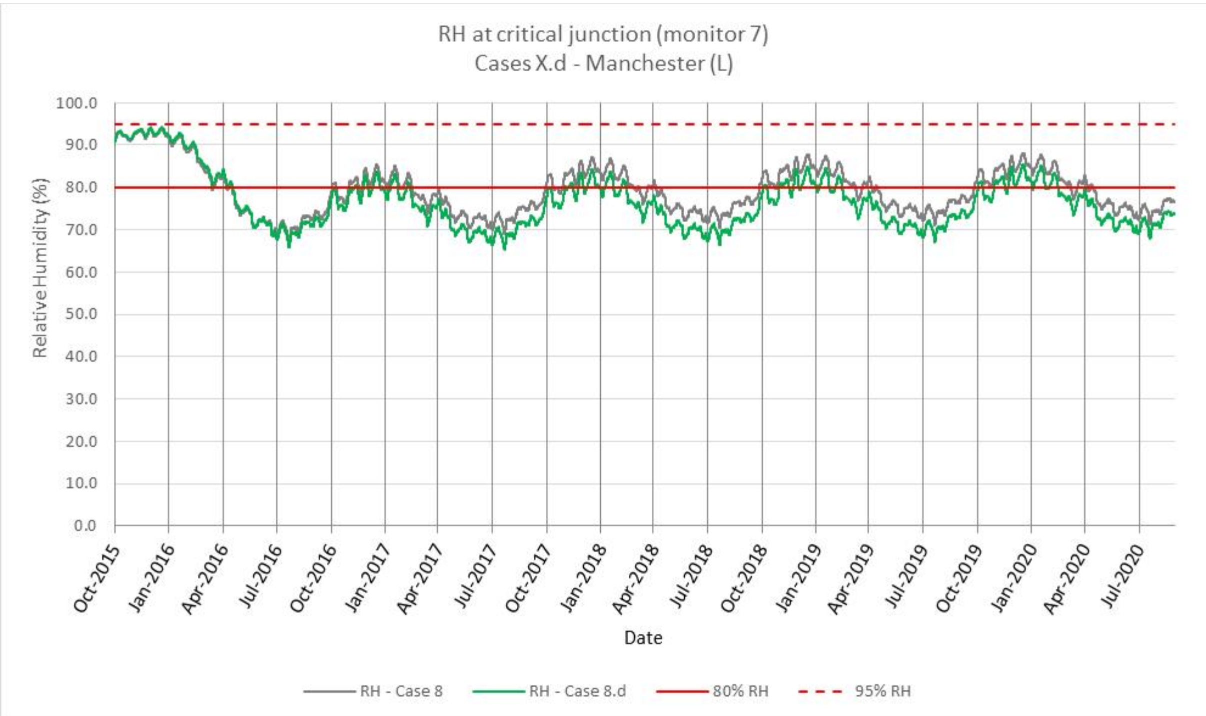


Figure 35: RH levels at critical junction for Cases 8 and 8d

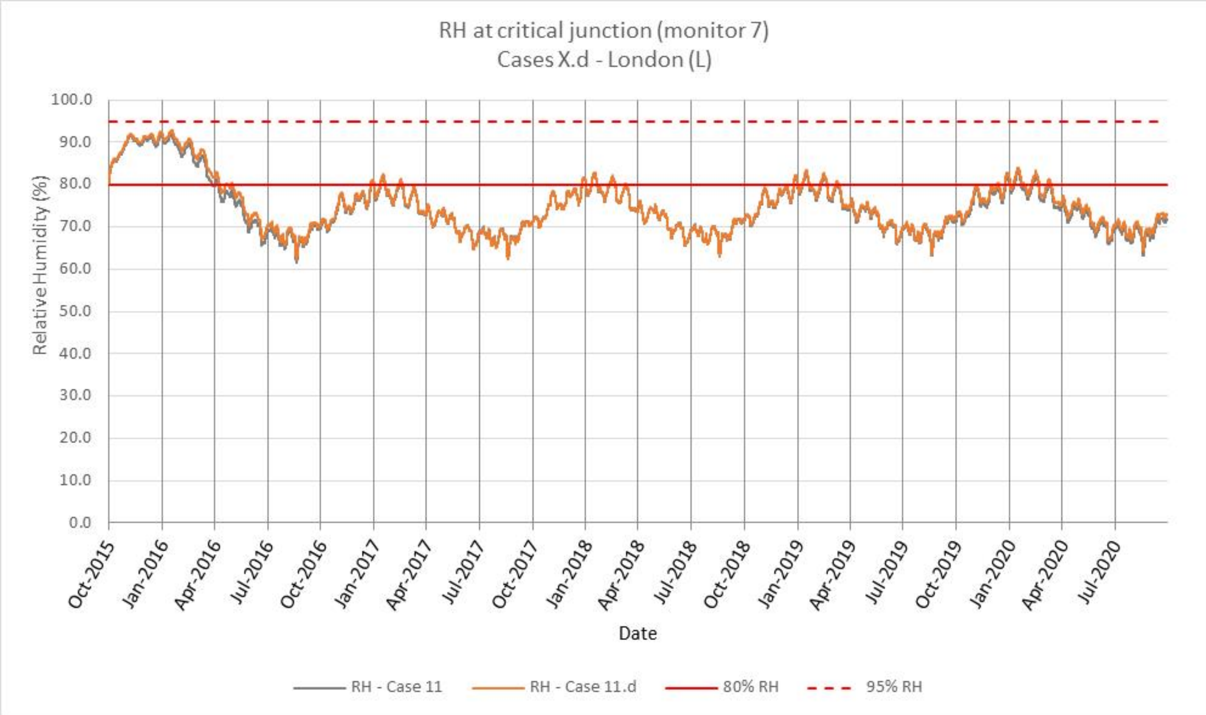


Figure 36: RH levels at critical junction for Cases 11 and 11.d

10.5.3. Conclusions – Sensitivity Analysis Cases X.d

<u>Moisture risk assessment criteria</u>

Similarly to the baseline cases, the RH threshold can be relaxed from 80% to 95% due to the conditions and materials present at the critical junction.

All cases achieve equilibrium, and the results show that the sensitivity analysis cases perform similarly to or better than the baseline cases. Indeed, RH levels at the critical junction for this sensitivity analysis are kept below or equivalent to the baseline RH levels. As all baseline cases were considered a ‘pass’, all sensitivity analysis cases are also considered a ‘pass’.

Results

The table below summarises the performance of the sensitivity analysis cases:

Table 13: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2.d Pass	Case 5.d Pass	Case 8.d Pass	Case 11.d Pass
Other	-	-	-	-

Effects of exposure zones

The graphs show that the presence of the DPM has a minimal impact on the hygrothermal performance of the build-up, with its impact decreasing with exposure zones being less exposed. Indeed, the London baseline and sensitivity analysis cases are indistinguishable from each other.

As the DPM is installed between the existing slab and the existing screed, the DPM is preventing any moisture present in the external environment to make its way through the build-up. This means that, with the impact of external conditions removed from the critical junction, all cases displays almost identical results despite being located in different wind-driven rain exposure zones. This finding is confirmed by the RH levels displayed on the graphs.

10.6. Conclusions

- Robust typology (good resistance to moisture), with 95% relaxed criteria, build-ups with insulation (Part L) considered ‘safe’ at equilibrium in all zones

11. Typology R5.1: Exposed floors – suspended timber floor Retrofit Measure: insulation between and below joists

The R5.1 typology is an exposed suspended timber floor that is uninsulated prior to retrofit. The retrofit measure is to install insulation between and below the timber joists.

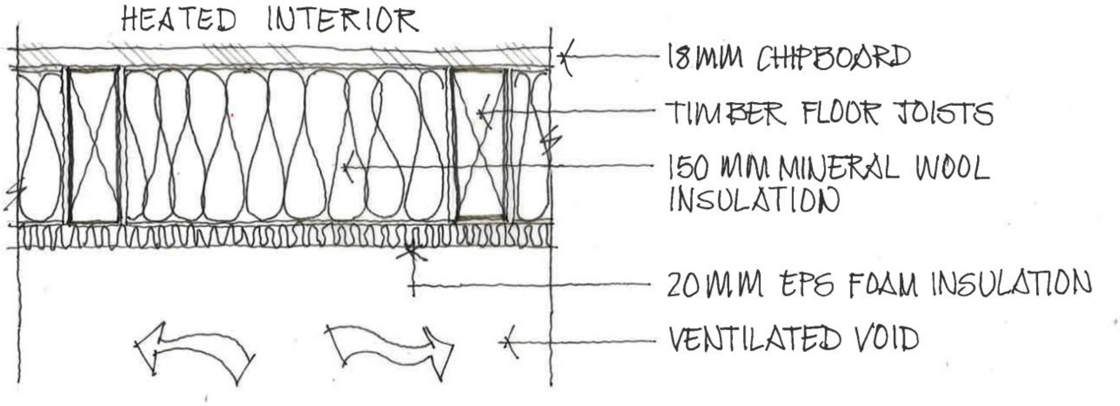


Figure 37: Illustration of the build-up of the typology with retrofit measure installed (Part C case) – rainscreen cladding not shown for clarity

11.1. Build-up

11.1.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 18mm chipboard
- 150mm uninsulated timber joists (above ventilated air space)

11.1.2. WUFI Build-up (post-retrofit)

Build-Up:

- 18mm chipboard
- 150mm mineral wool insulation (λ = 0.040 W/m.K) installed in between existing timber joists
- 20mm EPS foam insulation (λ = 0.040 W/m.K)

The build-up of R5.1 is identical to the Part C case in N5 of *Using numerical simulation to assess moisture risk in new constructions* report (Exposed suspended floor - insulated) with a slight variation in the thickness of the insulation layer. As this modelling work is assessing qualitatively the impact of different measures on the hygrothermal performance of each typology, this slight difference in insulation thickness does not have any consequential effect on the results.

The only other difference between the two typologies is the timing of the installation of the insulation layer. For N5, the insulation between the joists is installed simultaneously to the rest of the floor construction; whereas for R5.1, the insulation is retrofitted between the existing floor joists.

As part of the WUFI modelling process (in Section 3.4 of this report), a pre-retrofit build-up is supposed to be run to determine equilibrium levels. However, the pre-retrofit build-up for R5.1 is an uninsulated suspended timber floor. The materials present in the pre-retrofit build-up are not exposed to wind-driven rain and are not heavy weight materials. Therefore, it is not 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.

As no equilibrium model is required for R5.1, the initial conditions in the R5.1 WUFI model are identical to the N5 WUFI model. As a result, both R5.1 and N5 have the same WUFI input data and therefore share the same results, despite the difference in the timing of the installation of the insulation layer. For these reasons, no baseline or sensitivity modelling is performed on this typology and please refer to *Using numerical simulation to assess moisture risk in new constructions* Report for the results and analysis of typology N5 (Section 9).

12. Typology R5.2: Exposed floors – suspended timber floor Retrofit Measure: insulation below

The R5.2 typology is an exposed timber floor uninsulated prior to retrofit. The retrofit measure is to install rigid insulation below the existing soffit.

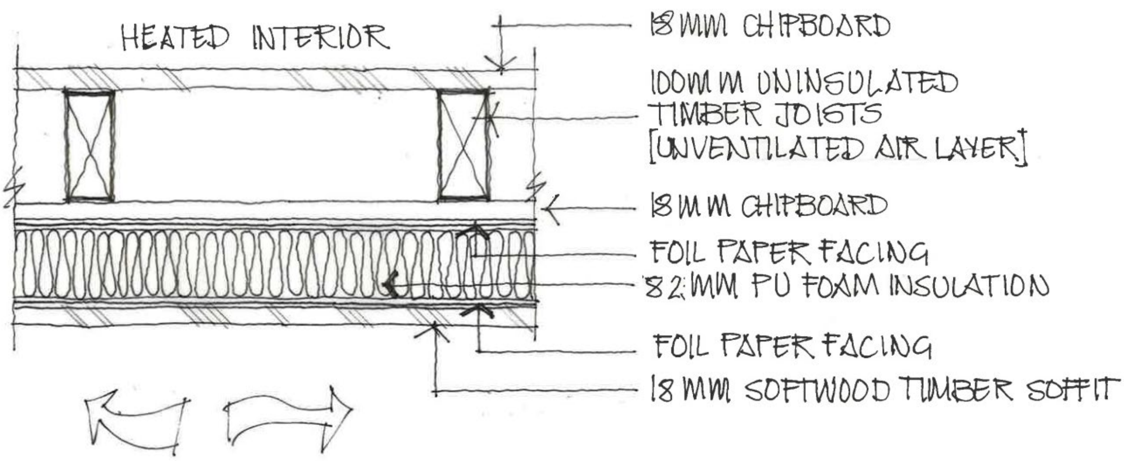


Figure 38: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

12.1. Assessment Method

As described in the STBA /DECC's Moisture Risk Assessment and Guidance (2014), *'floors of timber with a void beneath them should be ventilated to remove moisture'.* The underside is ventilated to outside, but the external surface of the build-up is not exposed directly to rain and solar radiation. Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method, as the main process driving moisture transfer in this build-up is vapour diffusion and the build-up is not exposed to wind-driven rain.

The results from the Glaser method analysis show that the post-retrofit build-up is considered to be a 'safe' build-up, with interstitial condensation occurring during the winter season, but evaporating completely during the summer months. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

12.2. Build-up

12.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 18mm chipboard
- 100mm uninsulated timber joists (above ventilated air space)
- 10mm cement board

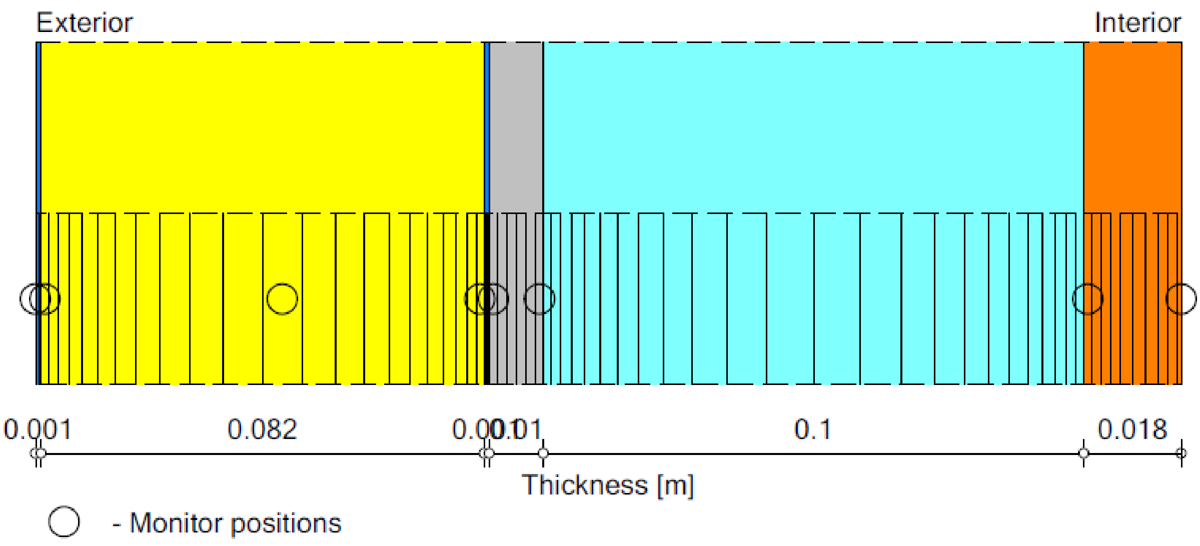
12.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are not exposed to wind-driven rain and are not heavy weight materials. Therefore, it is not 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)

Build-Up:

- 18mm chipboard
- 100mm uninsulated timber joists (unventilated air layer)
- 10mm cement board
- 1mm foil paper facing (sd = 14m)
- 82mm PU foam insulation (λ = 0.025 W/m.K) installed continuously below timber joists
- 1mm foil paper facing (sd = 14m)



Materials:

- *Foil paper facing (sd = 14m) (unlocked) 0.001 m
- *PU (heat cond.: 0,025 W/mK) 0.082 m
- *Foil paper facing (sd = 14m) (unlocked) 0.001 m
- Cement Board 0.01 m
- Air Layer 100 mm; without additional moisture capacity 0.1 m
- *Chipboard 0.018 m

12.3. Baseline Results

12.3.1. Baseline Cases

The 4 baseline cases are set across the four wind-driven rain exposure zones, meeting the Part L target U-value, as set out below.

Table 14: 4 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

12.3.2. Critical Junctions

Moisture problems tend to be exacerbated at interfaces, as they are locations at which moisture can accumulate or get trapped. For this typology, the focus is on the RH levels at the interface between the external foil layer and the cold side of the insulation. This critical junction is correctly identified in the BS EN ISO 13788 (2012) calculation.

An additional interface is also monitored, due to the presence of 'fragile' materials. The interface between the existing cement board soffit and the existing timber joists is therefore monitored, due to the presence of the timber joists. However, this interface is located on the warm side of the insulation and should not present any moisture risks (as shown with the BS EN ISO 13788 (2012) calculations). However, RH levels at this interface can already be predicted: this interface is kept on the warm side of the insulation. Therefore, the RH levels should be kept relatively 'safe'.

12.3.3. Graphs at Critical Junctions

The graphs displayed below show the RH levels for each location at the two critical / monitored junctions:

- The critical junction, being the interface between the external foil layer and the cold side of the insulation layer (listed as monitor 2 here)
- The additional monitored junction, being the interface between the existing cement board and the existing timber joists (listed as monitor 6)

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).

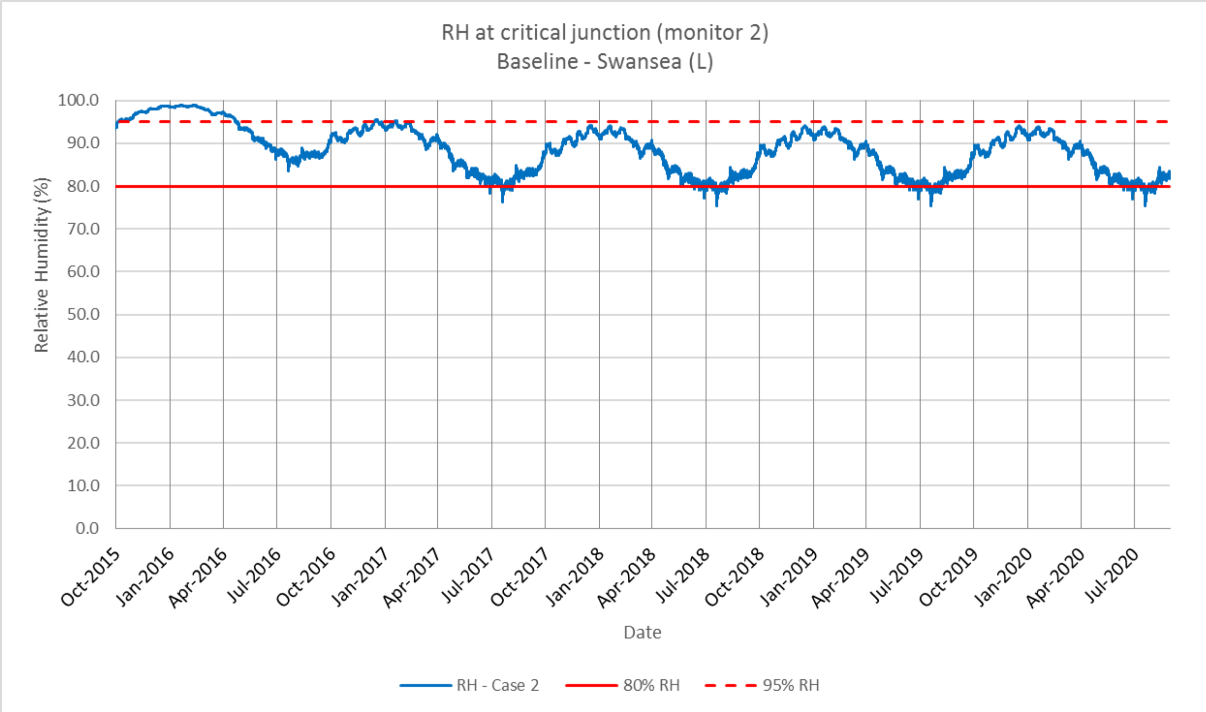


Figure 39: RH levels at critical junction (monitor 2) for Case 2

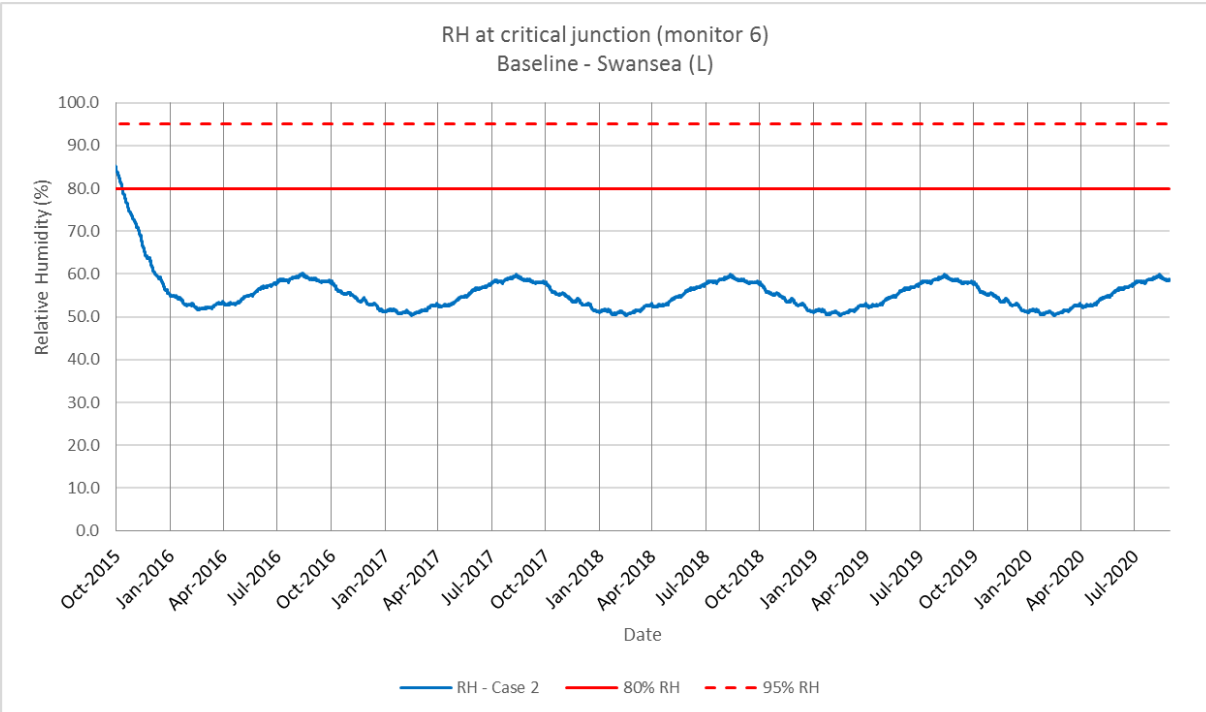


Figure 40: RH levels at monitored junction (monitor 6) for Case 2

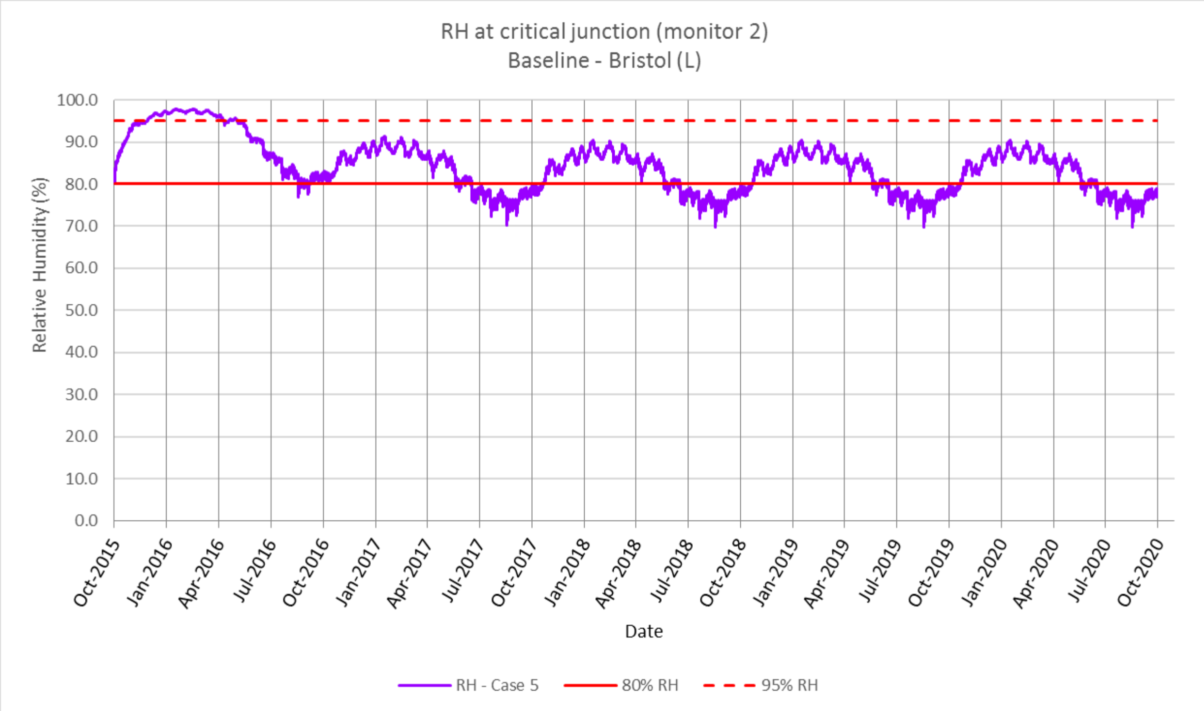


Figure 41: RH levels at critical junction (monitor 2) for Case 5

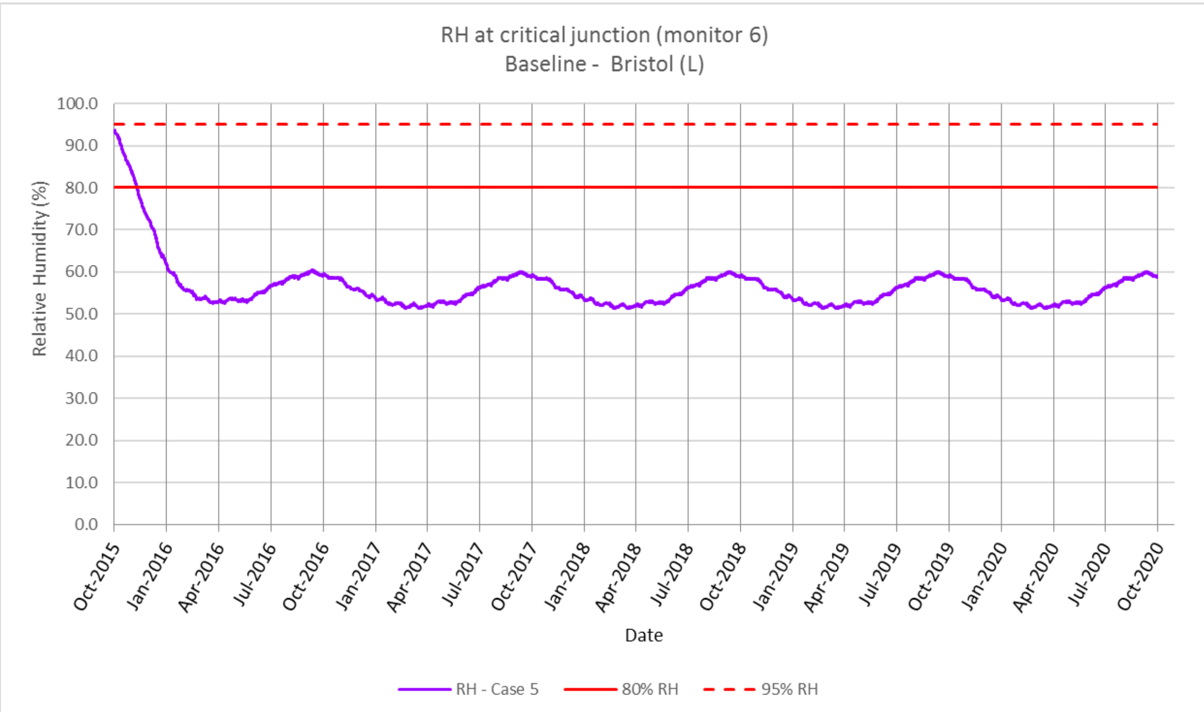


Figure 42: RH levels at monitored junction (monitor 6) for Case 5

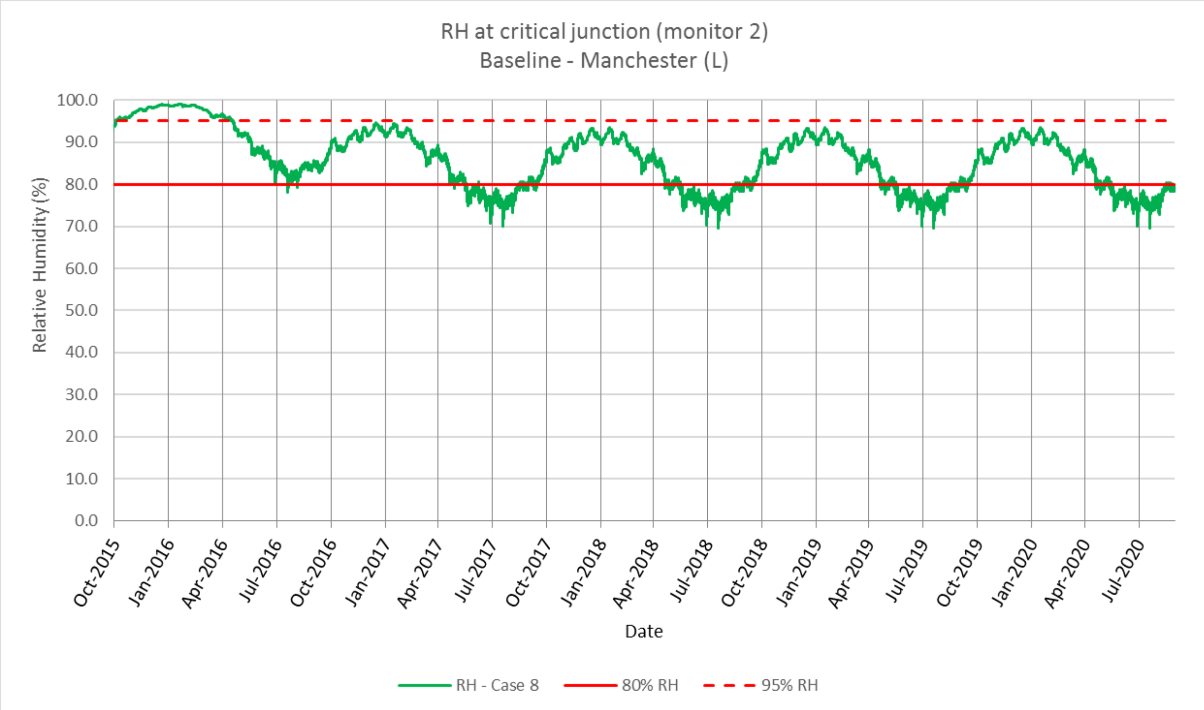


Figure 43: RH levels at critical junction (monitor 2) for Case 8

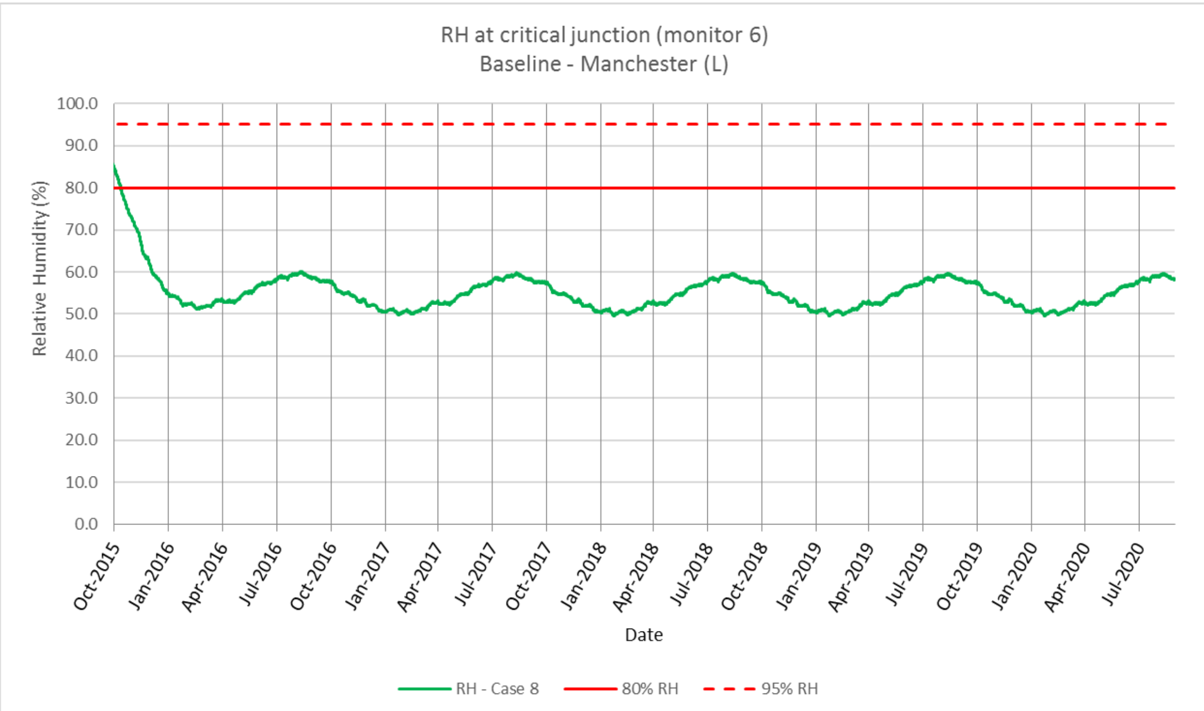


Figure 44: RH levels at monitored junction (monitor 6) for Case 8

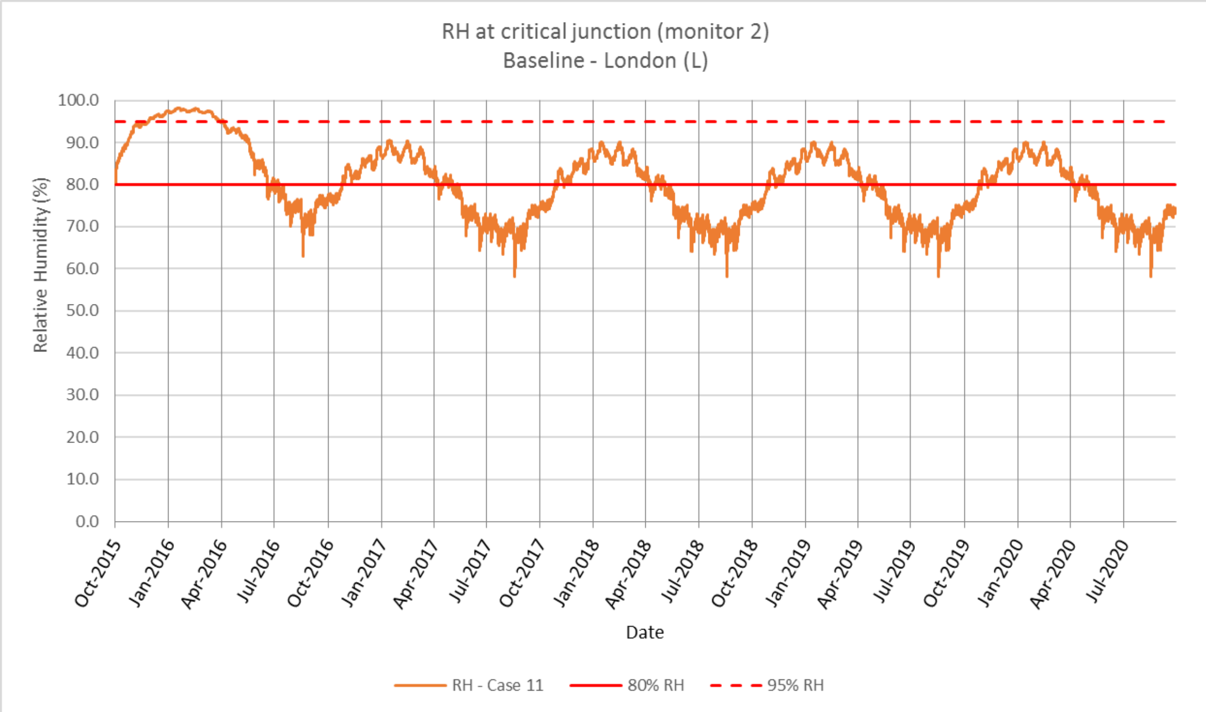


Figure 45: RH levels at critical junction (monitor 2) for Case 11

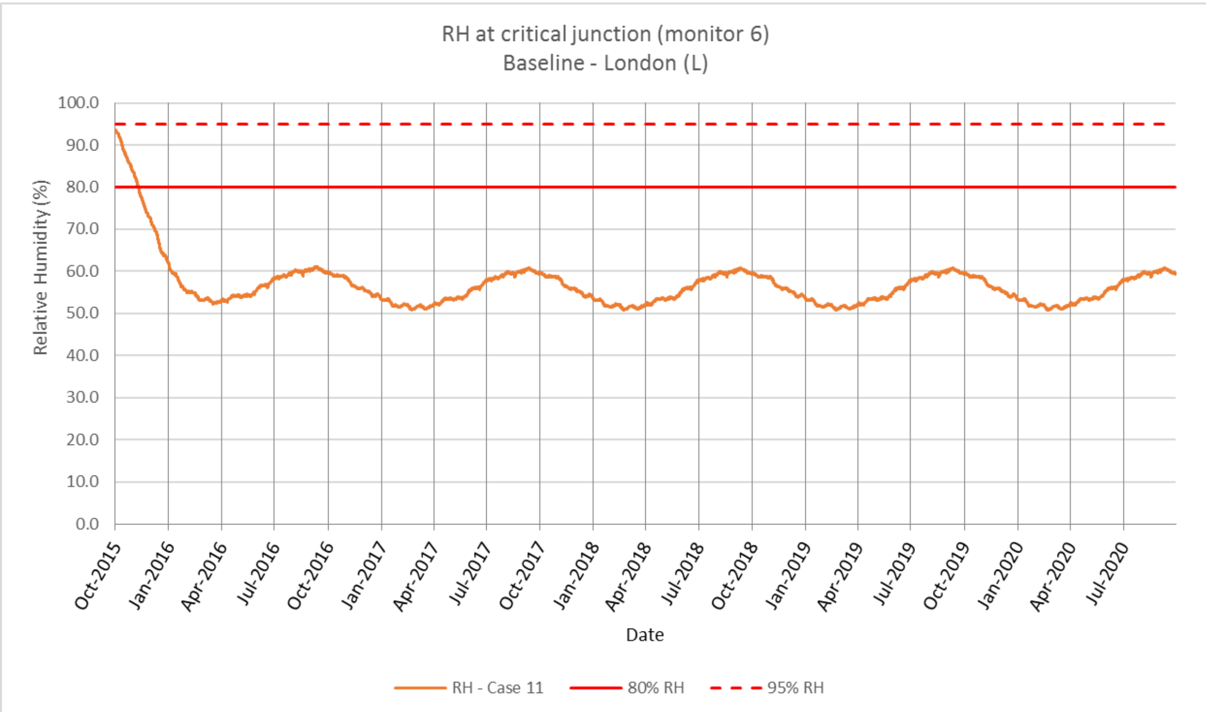


Figure 46: RH levels at monitored junction (monitor 6) for Case 11

12.3.4. Results Analysis

The critical level of 80% has been maintained for monitor 6, as timber is present at this interface. However, the RH threshold can be relaxed from 80% to 95% as there are no ‘fragile’ materials at this interface, no air should be present between the foil layer and the insulation it is attached too and this interface is separated from the internal space.

Moisture risk assessment criteria

All scenarios achieve equilibrium (which means that moisture does not accumulate over time). As predicted, all cases at the monitor 6 show RH levels at the interface between the cement board soffit and the unventilated layer being well within the recommended 80% RH limit.

RH levels at the critical junction (monitor 2), between the external foil layer and the insulation layer, display initial conditions above the 95% RH limit for several months during the first year, due to high initial moisture conditions. But all cases show RH levels stabilising at equilibrium with RH levels kept below the 95% RH threshold throughout the year. Therefore, as all cases display high RH levels only initially, before staying within recommended levels at equilibrium, all cases are considered a ‘pass’.

Results

These results are summarised in the table below.

Table 15: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
Other	-	-	-	-

Effects of exposure zones

As the build-up is not exposed to the elements, the difference in exposure zone has a minor effect on its hygrothermal performance. The difference in RH levels can be explained by the difference in external conditions (temperature and RH levels) in the four exposure zones.

12.4. Conclusions

- The results agree with calculations done following the BS EN ISO 13788 (2012) method, which demonstrates no interstitial condensation risk in this build-up.
- This build-up is sheltered from the elements and moisture driven by vapour diffusion, so theoretically safe
- Safe construction, but high moisture levels on the external side of the construction (which is the external side of insulation and could lead to reduced thermal performance)
- AVCL (or taping of foil) likely to be needed to address likely gaps/cracks in insulation layer

13. Typology R6: Exposed upper floors - concrete (uninsulated) Retrofit Measure: insulation above

The R6 typology is an exposed concrete slab. The retrofit measure is to add PU foam insulation with a chipboard finish internally, above the existing concrete screed.

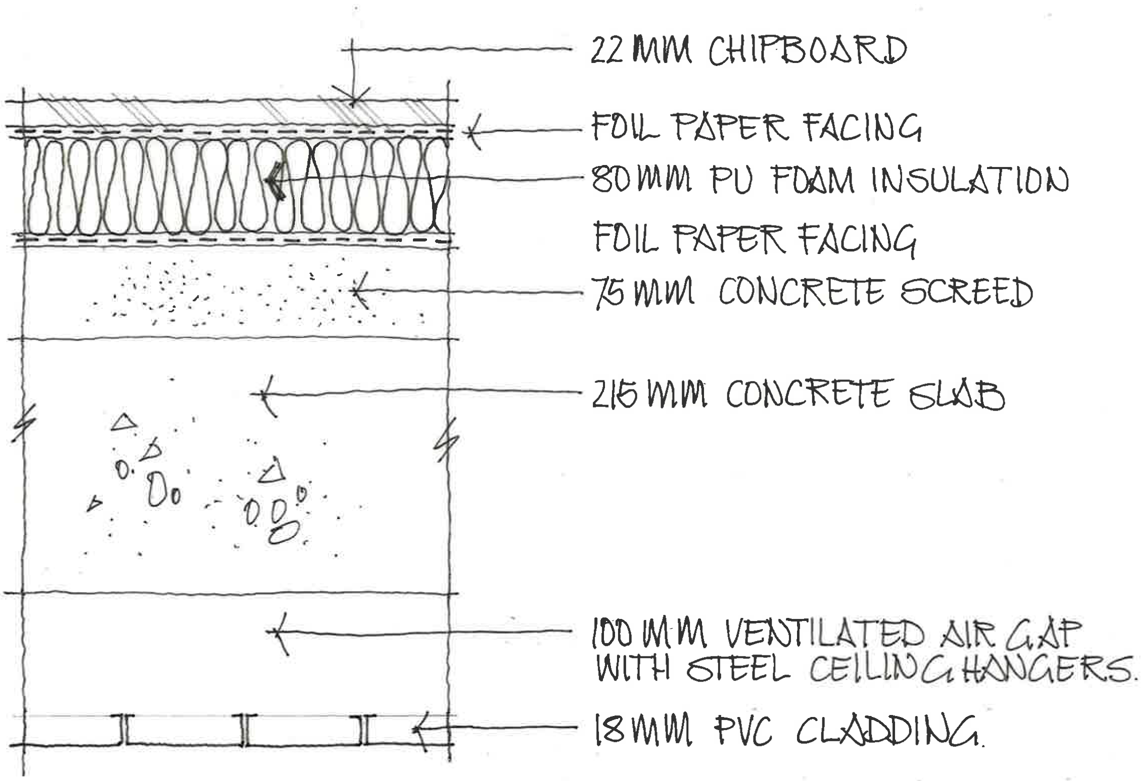


Figure 47: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

13.1. Assessment Method

As the STBA's/DECC's Moisture Risk Assessment and Guidance (2014) document states, *'floors of structural concrete with a void beneath them should be ventilated to remove moisture'*.

As the concrete slab layer is therefore partially exposed (underside concrete is submitted to external temperatures and RH levels due to the ventilated gap between the concrete slab and the cladding, but without being submitted to the wind-driven rain or solar gains), the movement of moisture in this build-up is driven by vapour diffusion. This mechanism is dealt with in the BS EN ISO 13788 (2012) calculation method, and therefore this method could be used to provide an accurate assessment.

The results by the Glaser method show that this retrofit measure is considered ‘risky’, with the occurrence of interstitial condensation between the screed and the newly installed insulation, which does not evaporate completely during the summer months. The results regarding interstitial condensation and its potential accumulation will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

13.2. Build-up

13.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 75mm concrete screed
- 215mm concrete slab
- 100mm ventilated air gap with stainless steel ceiling hangers *(considered outside of the WUFI build-up)*
- 18mm PVC cladding *(considered outside of the WUFI build-up)*

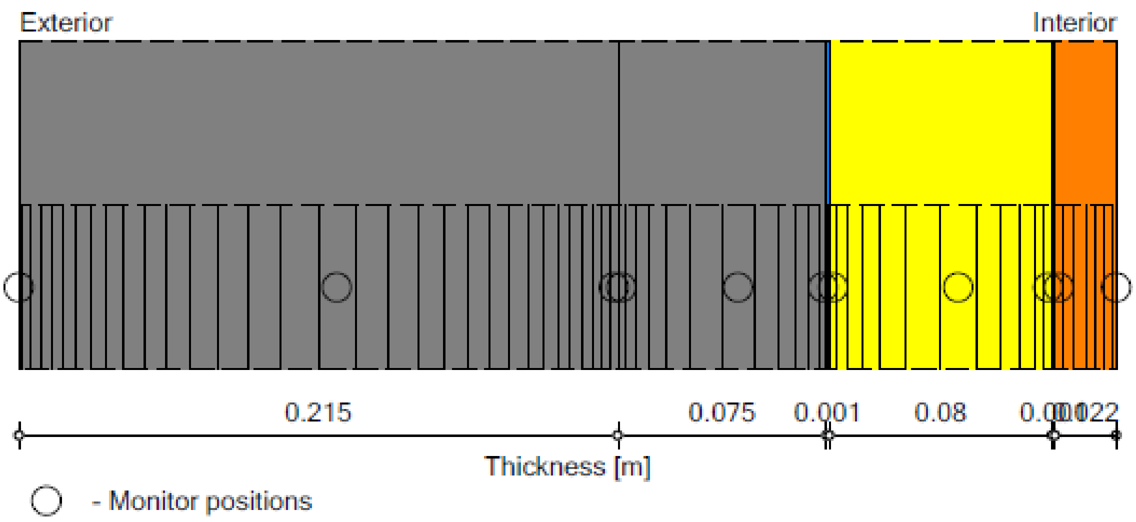
13.2.2. Initial Conditions

Although the materials present in the pre-retrofit build-up are not exposed to wind-driven rain, the concrete slab and screed are heavy weight materials, 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)

Build-Up:

- 22mm chipboard
- 1mm foil paper facing (sd = 14m)
- 80mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 75mm concrete screed
- 215mm concrete slab
- 100mm ventilated air gap with stainless steel ceiling hangers *(considered outside of the WUFI build-up)*
- 18mm PVC cladding *(considered outside of the WUFI build-up)*



Materials:

(grey)	- Concrete, C35/45	0.215 m
(grey)	- Concrete Screed, mid layer	0.075 m
(blue)	- *Foil paper facing (sd = 14m) (unlocked)	0.001 m
(yellow)	- *PU (heat cond.: 0,025 W/mK)	0.08 m
(blue)	- *Foil paper facing (sd = 14m) (unlocked)	0.001 m
(orange)	- *Chipboard	0.022 m

<u>WUFI Input Parameters</u>

As the soffit void is considered ventilated, the ventilated air gap and PVC cladding 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 concrete slab) is exposed to different external conditions due to the ventilated soffit void acting as a protective layer against wind-driven rain.

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
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)

13.3. Baseline Results

13.3.1. Baseline Cases

The 4 baseline cases are set across the four wind-driven rain exposure zones, meeting the Part L target U-value, as set out below.

Table 16: 4 baseline cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

13.3.2. Critical and Monitored Junctions

For this typology, the focus is given on RH levels at the interface of the cold concrete screed and insulation. Indeed, paragraph F.4.2 in BS 5250 (2011) states that *'when insulation is applied above the slab, there is no risk of surface condensation but interstitial condensation is likely to occur on the upper surface of the slab. To avoid that risk, an AVCL should be laid between the thermal insulation and the floor finish'*. This critical junction is correctly identified in the BS EN ISO 13788 (2012) calculation.

It is important to note that the insulation also has foil layers on both sides, which are significant barriers to moisture movement, with one of them present at the identified critical junction. As vapour transfer mainly occurs through vapour diffusion in this build up (i.e. from inside to outside in winter season), the foil layer significantly reduces the possibility of moisture accumulation at the critical interface previously mentioned. Therefore, RH levels should be safer at the critical junction (i.e. between the existing concrete screed and the foil layer) than on the other side of the foil layer (i.e. between the foil layer and the insulation layer itself). As such, the results from an additional monitor, on the other side of the foil layer, need to be examined to get a clearer picture of the potential risks at this junction.

13.3.3. Graphs at Critical Junction

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

- The interface between the existing concrete screed and the external foil layer (listed as monitor 6 here)
- The interface between the external foil layer and the insulation (listed as monitor 7)

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).

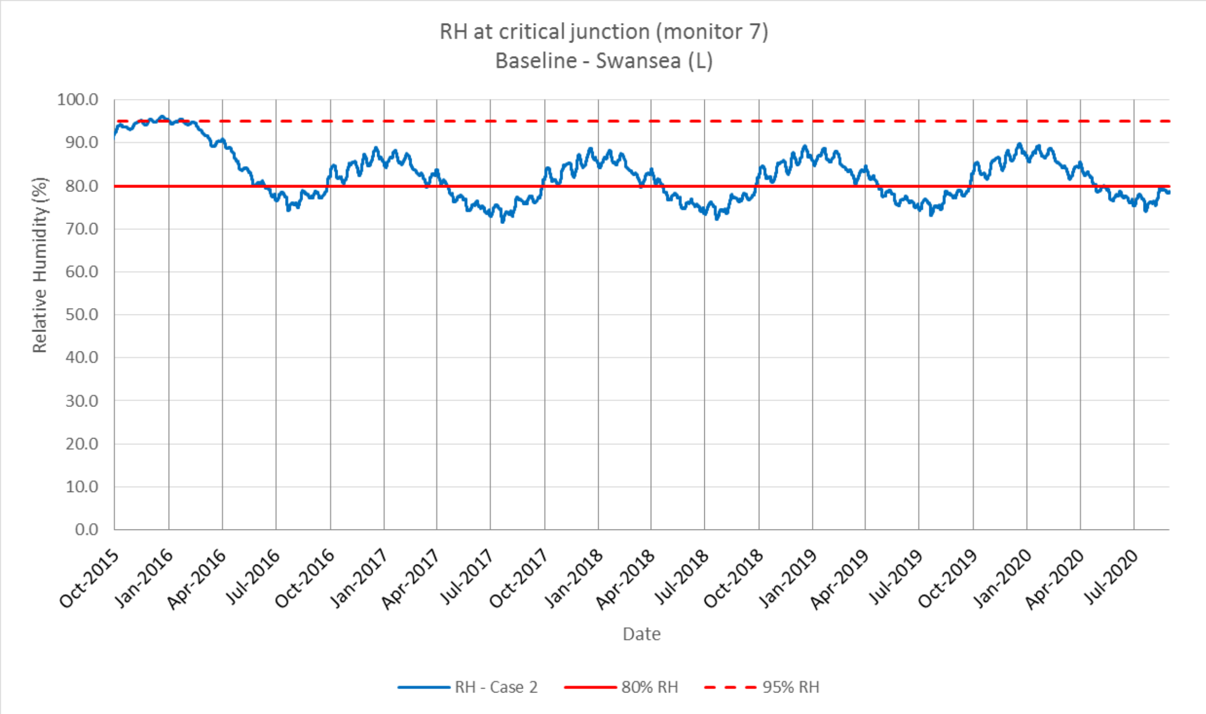


Figure 48: RH levels at critical junction (monitor 7) for Case 2

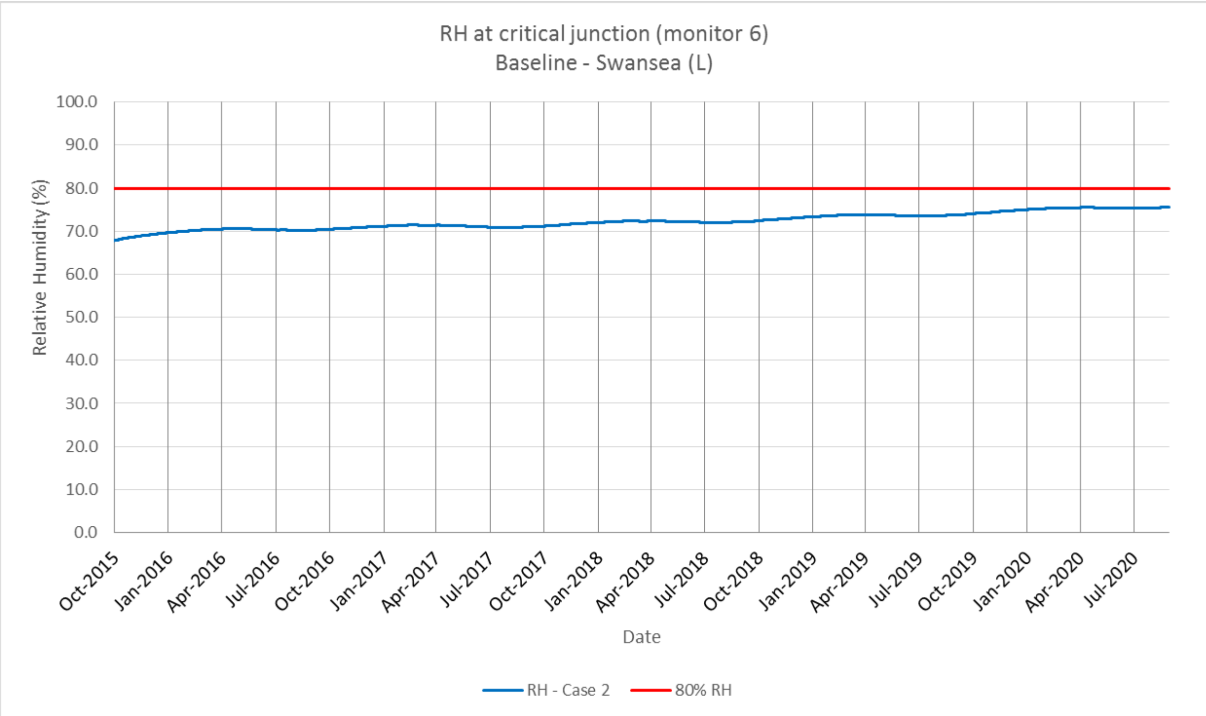


Figure 49: RH levels at critical junction (monitor 6) for Case 2

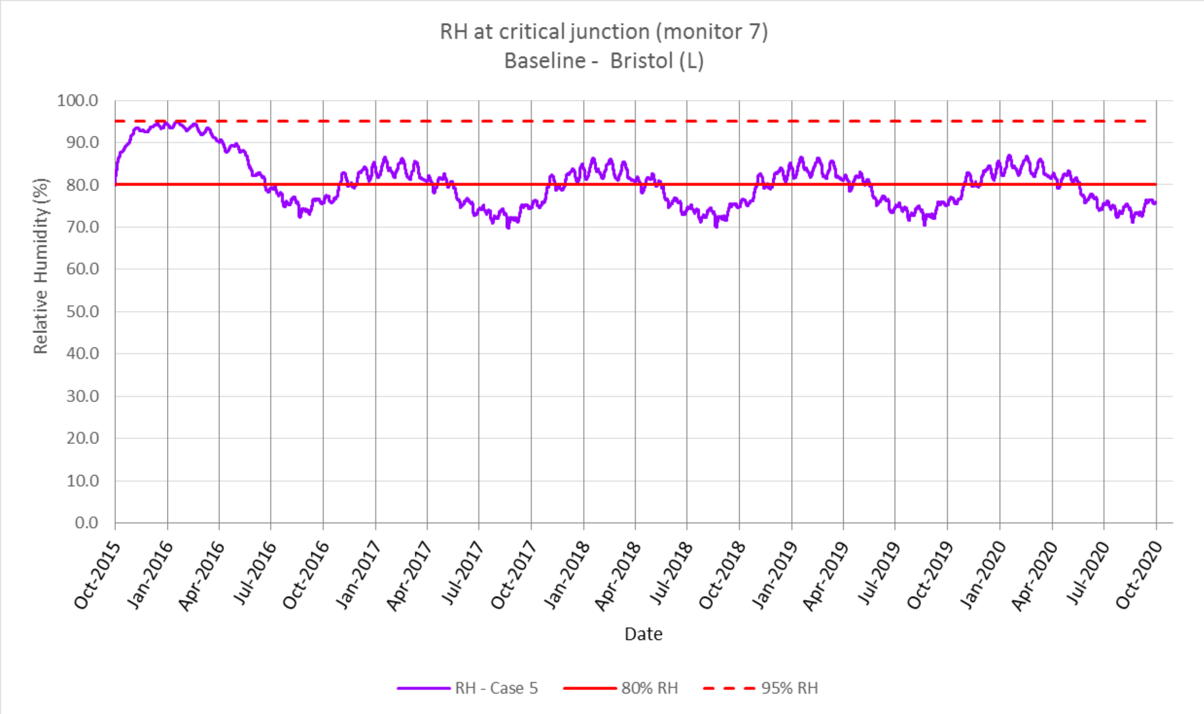


Figure 50: RH levels at critical junction (monitor 7) for Case 5

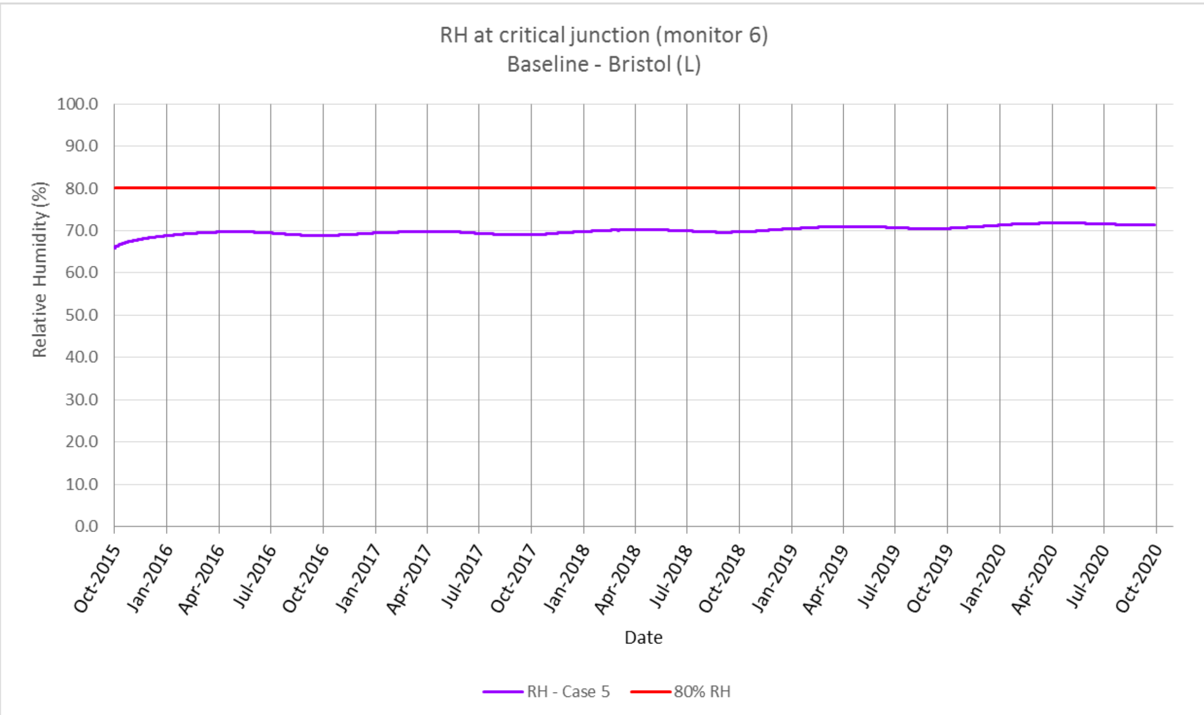


Figure 51: RH levels at critical junction (monitor 6) for Case 5

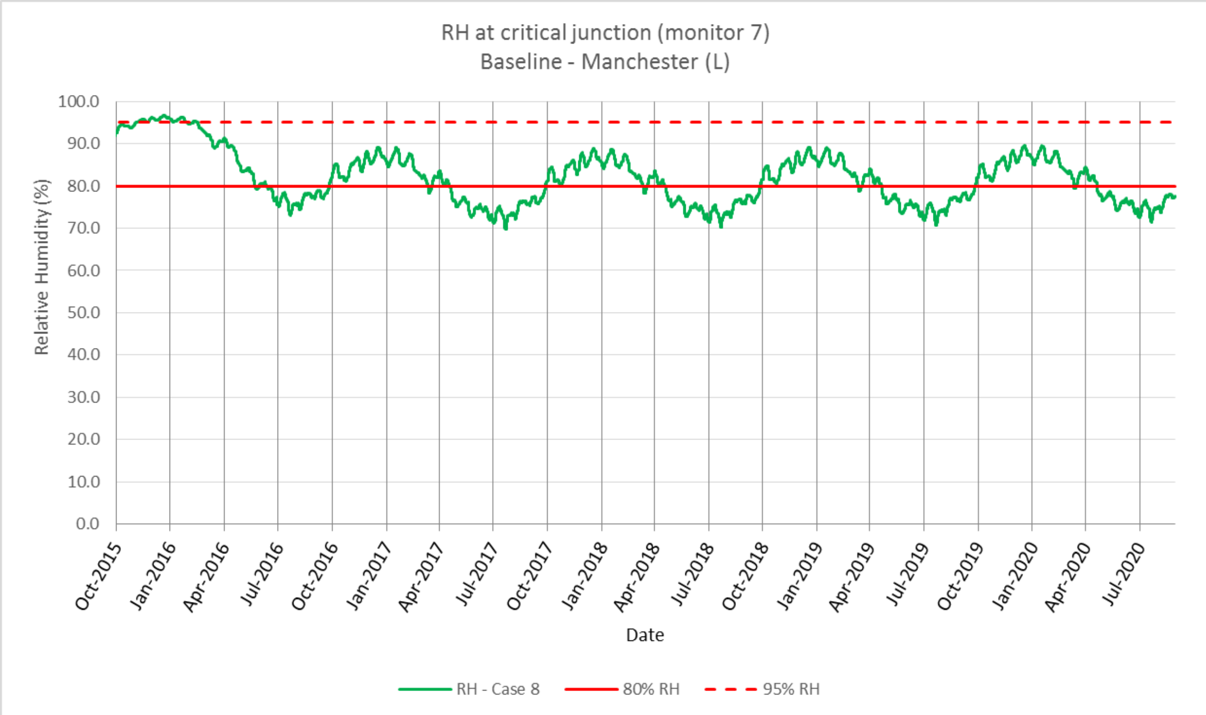


Figure 52: RH levels at critical junction (monitor 7) for Case 8

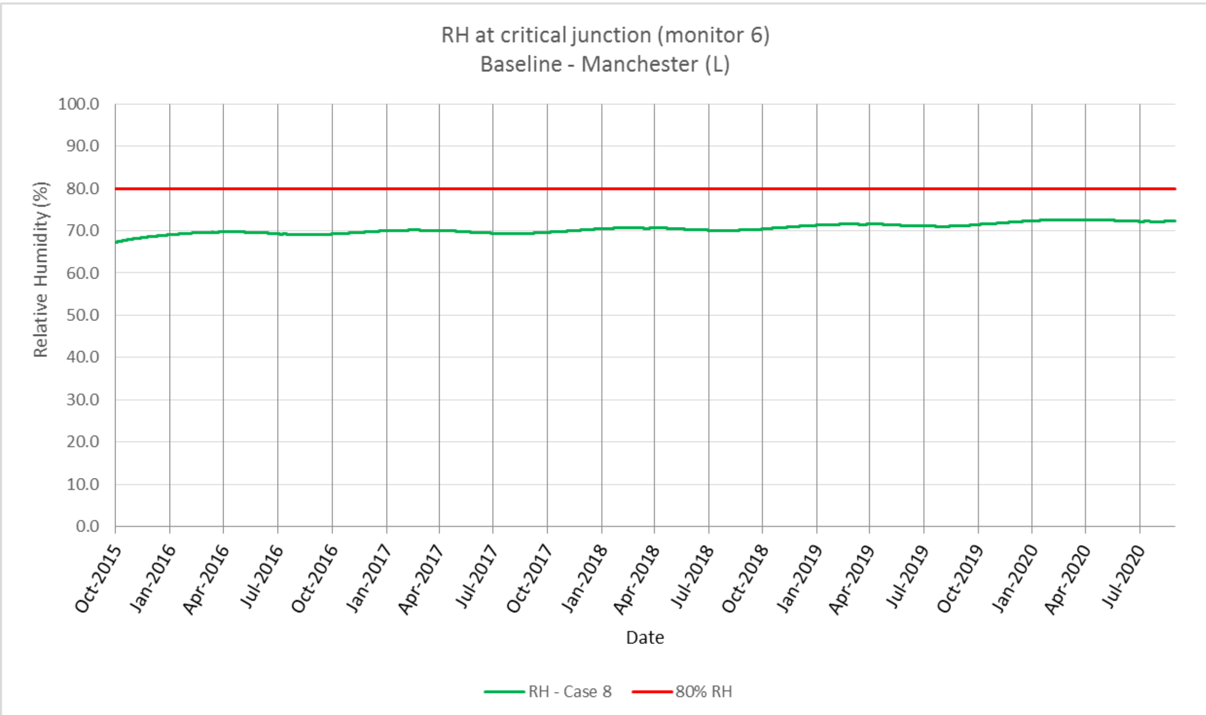


Figure 53: RH levels at critical junction (monitor 6) for Case 8

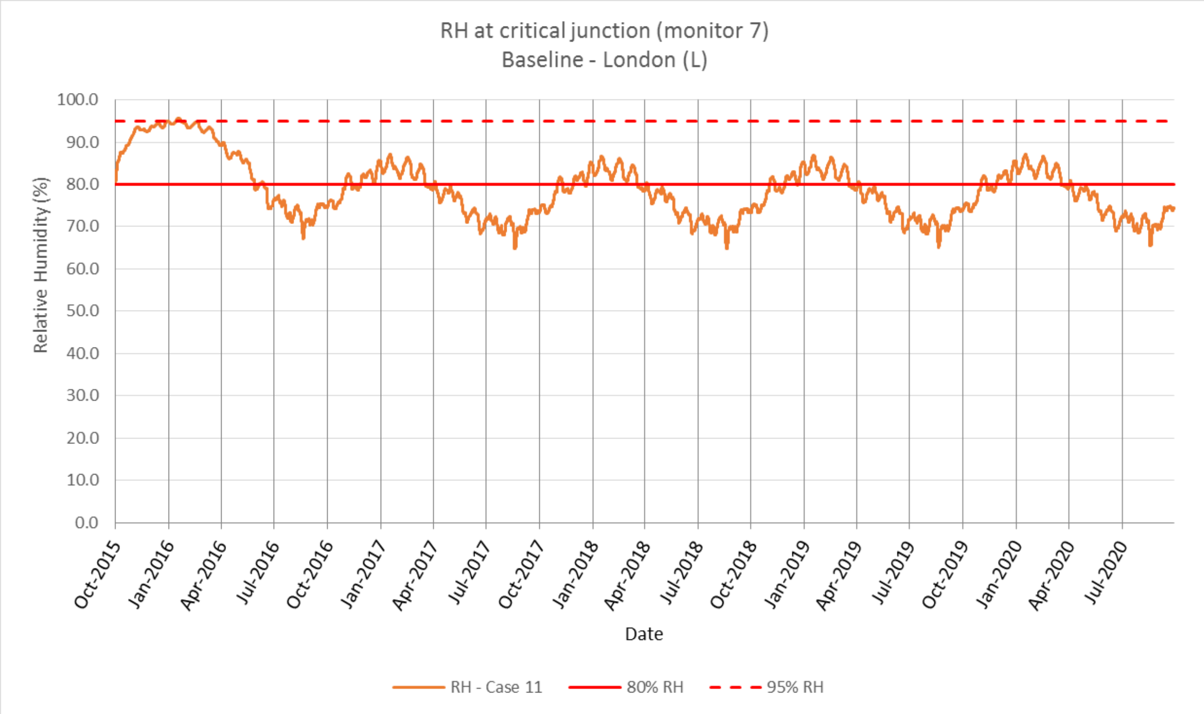


Figure 54: RH levels at critical junction (monitor 7) for Case 11

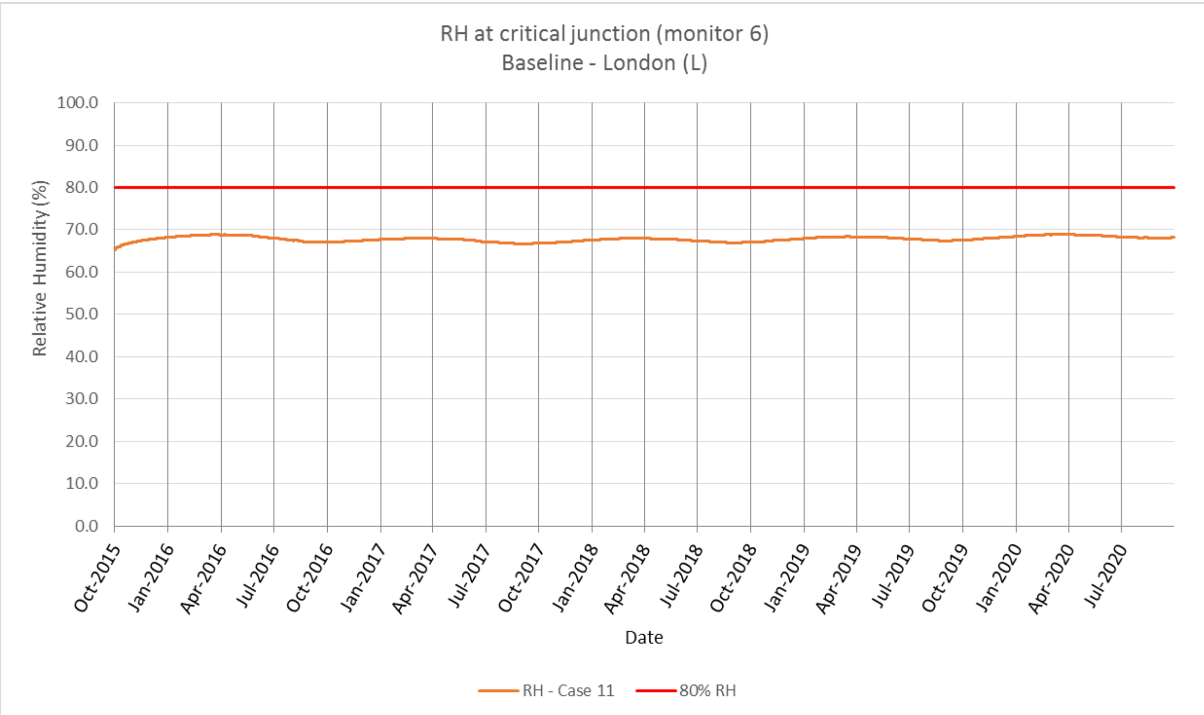


Figure 55: RH levels at critical junction (monitor 6) for Case 11

13.3.4. Results Analysis

For both monitored junctions, the RH threshold can be relaxed from 80% to 95% as there are no ‘fragile’ materials at this interface, in addition to the fact that no air or food for mould growth should be present at these interfaces.

Moisture risk assessment criteria

At the first interface (monitor 7 being the most at risk) between the external foil layer and the insulation, the RH levels are kept significantly below the 95% RH threshold (except for a few months during the first year of modelling, where RH levels reach 95% due to high initial conditions).

As predicted, the RH levels at the second interface (monitor 6) between the existing concrete screed and the external foil layer, display much lower RH levels than those at monitor 7. This is due to the protection provided by the foil layer at this interface, significantly reducing the amount of water vapour allowed to move via diffusion through the build-up and reach this second interface. This means that all cases are considered a 'pass'.

The RH levels at this second interface (monitor 6) do not fully reach equilibrium on the graphs above. However, these cases have been rerun for a prolonged period of 40 years, which show that RH levels do not go above the 95% RH threshold at any given time and the RH levels stabilise (at different levels for each case) after a period of around 20 years.

Results

The table below summarises the performance of the sensitivity analysis cases:

Table 17: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	-	-	-	-
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
Other	-	-	-	-

Effects of exposure zones

As the build-up is not exposed to the elements, the difference in exposure zone has a minor effect on its hygrothermal performance. The minor difference in RH levels at the critical junctions can be explained by the difference in external conditions (temperature and RH levels) in the four exposure zones.

13.4. Conclusions

- The results do not agree with calculations done following the BS EN ISO 13788 (2012) method, which states that interstitial condensation accumulates over time in this build-up at the critical junction.

14. Typology R7: Exposed floors - concrete (uninsulated) Retrofit Measure: insulation below

The R7 typology is a suspended concrete slab that is uninsulated prior to retrofit. The retrofit measure is to install insulation below the existing slab.

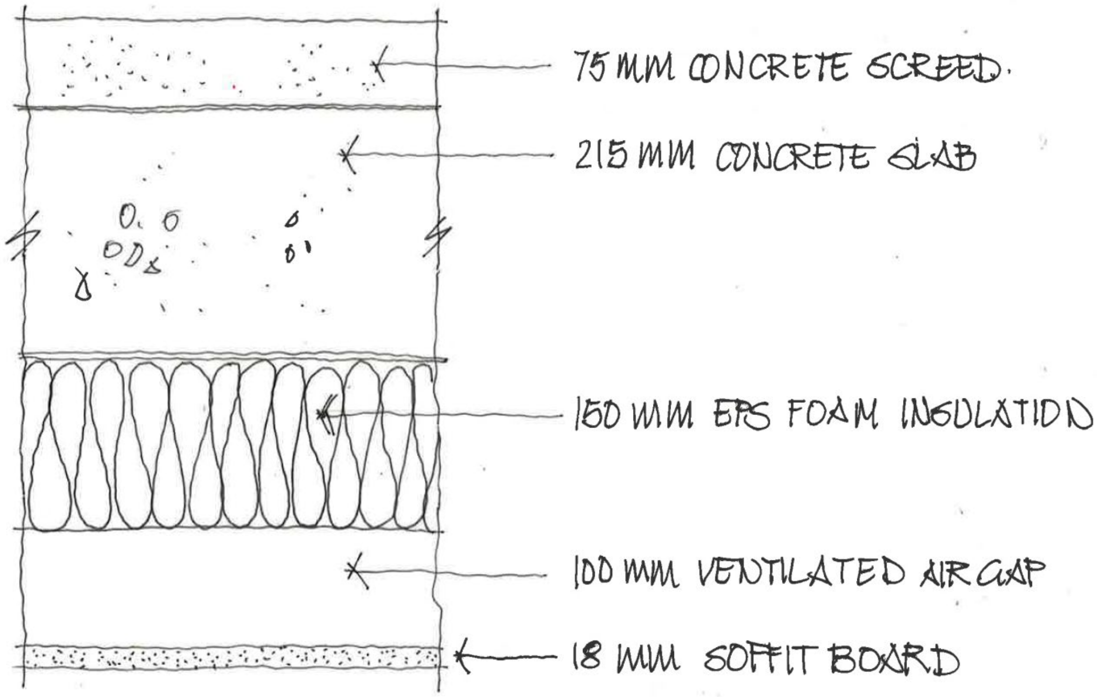


Figure 56: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

14.1. Build-up

14.1.1. WUFI Build-up (pre-retrofit)

<u>Build-Up:</u>

- 75mm concrete screed
- 215mm concrete slab
- 100mm ventilated air gap with stainless steel ceiling hangers *(considered outside of the WUFI build-up)*
- 18mm PVC cladding *(considered outside of the WUFI build-up)*

14.1.2. WUFI Build-up (post-retrofit)

Build-Up:

- 75mm concrete screed
- 215mm concrete slab
- 150mm EPS foam insulation (λ = 0.040 W/m.K)
- 100mm ventilated air gap with stainless steel ceiling hangers *(considered outside of the WUFI build-up)*
- 18mm PVC cladding *(considered outside of the WUFI build-up)*

The build-up of R7 is identical to Part L case in N7 of *Using numerical simulation to assess moisture risk in new constructions* report (Exposed concrete floor - insulated below).

The only difference between the two typologies is the timing of the installation of the insulation layer. For N7, the insulation is installed simultaneously to the rest of the floor construction; whereas for R7, the insulation is retrofitted below the existing concrete slab.

As part of the WUFI modelling process (in Section 3.4 of this report), a pre-retrofit build-up is supposed to be run to determine equilibrium levels. However, the pre-retrofit build-up for R7 is an uninsulated concrete floor. The concrete layer present in the pre-retrofit build-up is drier than it would be in a new-build construction scenario, as it has had enough time to dry to the inside of the property (assuming adequate temperature and RH levels internally). This means that using default values for the initial moisture contents of materials in the WUFI modelling of N7 of *Using numerical simulation to assess moisture risk in new constructions* report is a worse scenario, when compared to the R7 pre-retrofit model. Therefore, it is not 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.

As no equilibrium model is required for R7, the initial conditions in the R7 WUFI model are identical to the N7 WUFI model. As a result, both R7 and N7 have the same WUFI input data and therefore share the same results, despite the difference in the timing of the installation of the insulation layer. For these reasons, no baseline or sensitivity modelling is performed on this typology and please refer to *Using numerical simulation to assess moisture risk in new constructions* Report for the results and analysis of typology N7.

15. Typology R8: Solid masonry wall Retrofit Measure: Internal 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 closed-cell insulation.

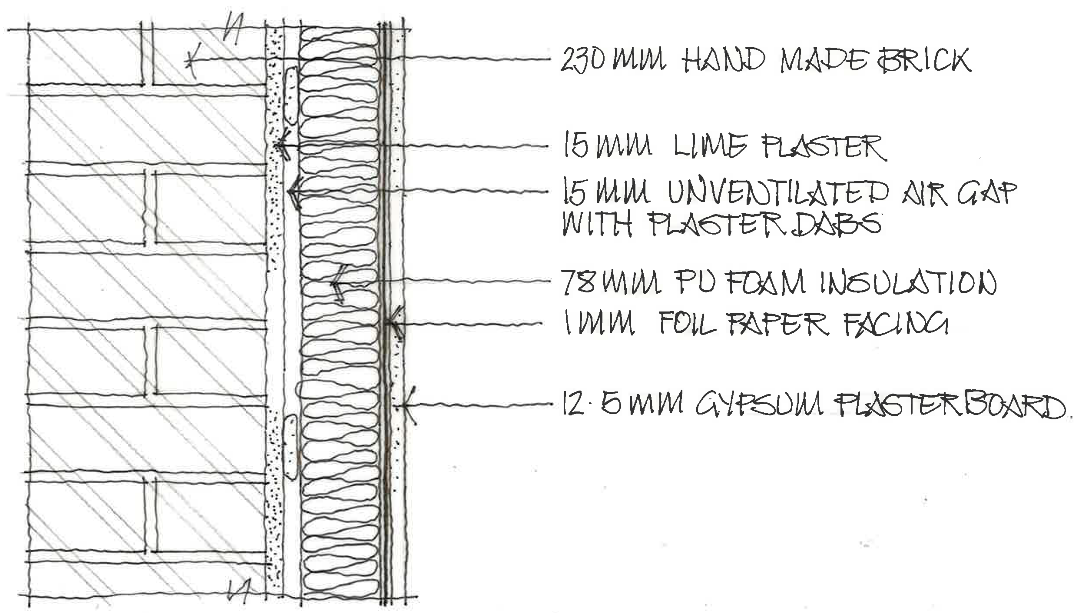


Figure 57: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

15.1. 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. Indeed, the analysis of this build-up with the Glaser method shows no presence of interstitial condensation, while this construction is known to be a risky construction in the industry currently.

Similarly, the STBA/DECC's ‘Moisture Risk Assessment and Guidance’ (2014) document notes 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)*.’

Due to the limitations of previous methods to assess accurately the hygrothermal performance of this build-up, 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)

Build-Up:

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

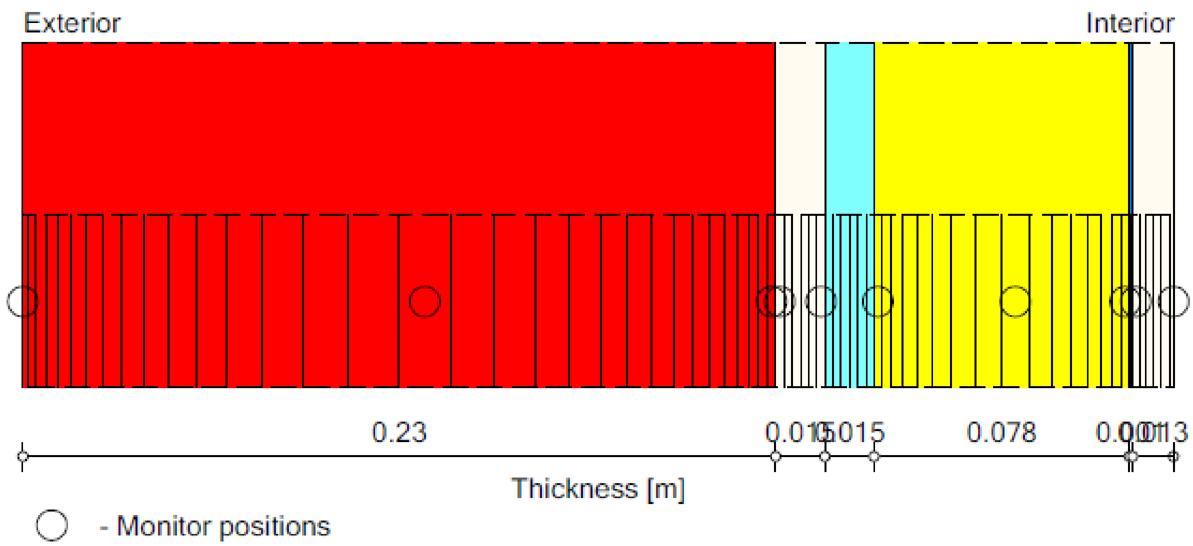
15.2.2. Initial Conditions

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.

15.2.3. WUFI Build-up (post-retrofit)

Build-Up:

- 230mm solid brick (WUFI material: solid brick (hand-formed))
- 15mm lime plaster (assumed no wallpaper finish)
- 15mm unventilated air layer with plaster dabs
- 78mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 12.5mm gypsum plasterboard



Materials:

	- Solid Brick, hand-formed	0.23 m
	- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)	0.015 m
	- *Air Layer 15 mm; without additional moisture capacity (unlocked)	0.015 m
	- *PU (heat cond.: 0,025 W/mK)	0.078 m
	- *Foil paper facing (sd = 14m)	0.001 m
	- *Gypsum Board	0.013 m

<u>Material Physical Properties</u>

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.

Sensitivity Analysis

As the brick’s physical characteristics play a significant role in the hygrothermal performance of this build-up, in addition to the lack of data available for UK bricks, the first sensitivity analysis is carried out with a substitution of the default bricks by two additional bricks with different physical characteristics (density, porosity and water absorption coefficient), described in the section 15.4.1.

15.3. Baseline Results

15.3.1. Baseline Cases

The 8 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 18: 4 baseline cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1	Case 4	Case 7	Case10
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

15.3.2. 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'*.

15.3.3. 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).

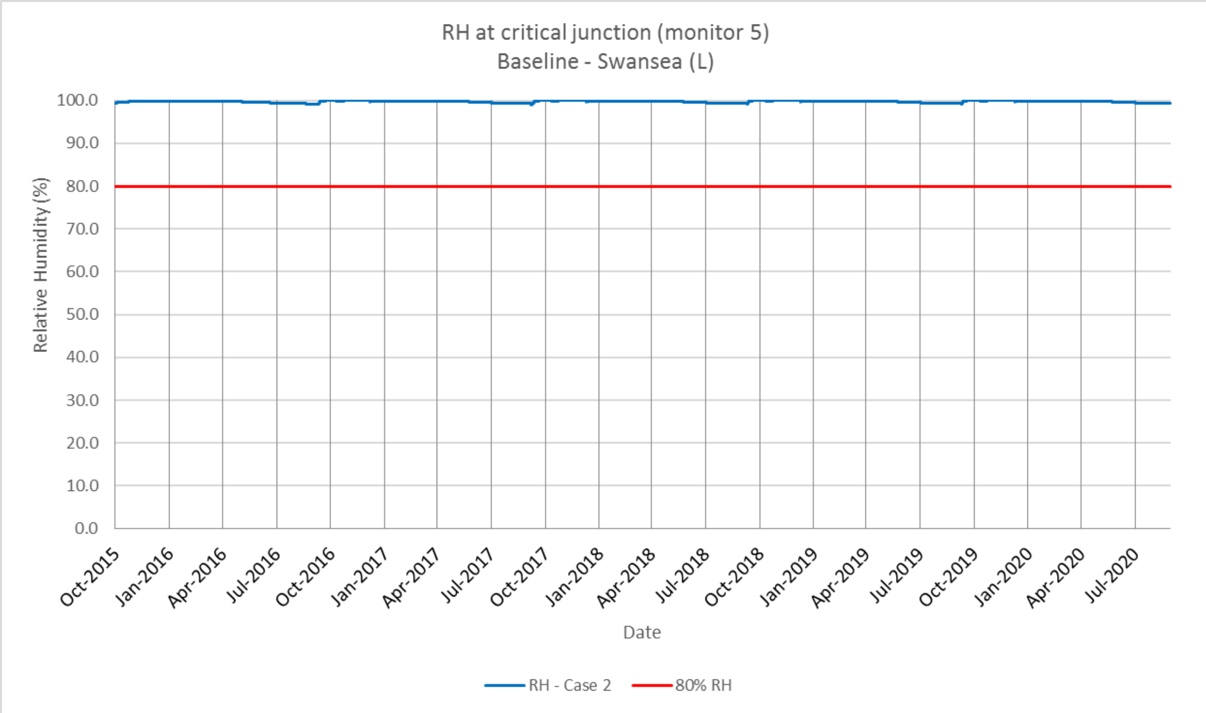


Figure 58: RH levels at critical junction for Case 2

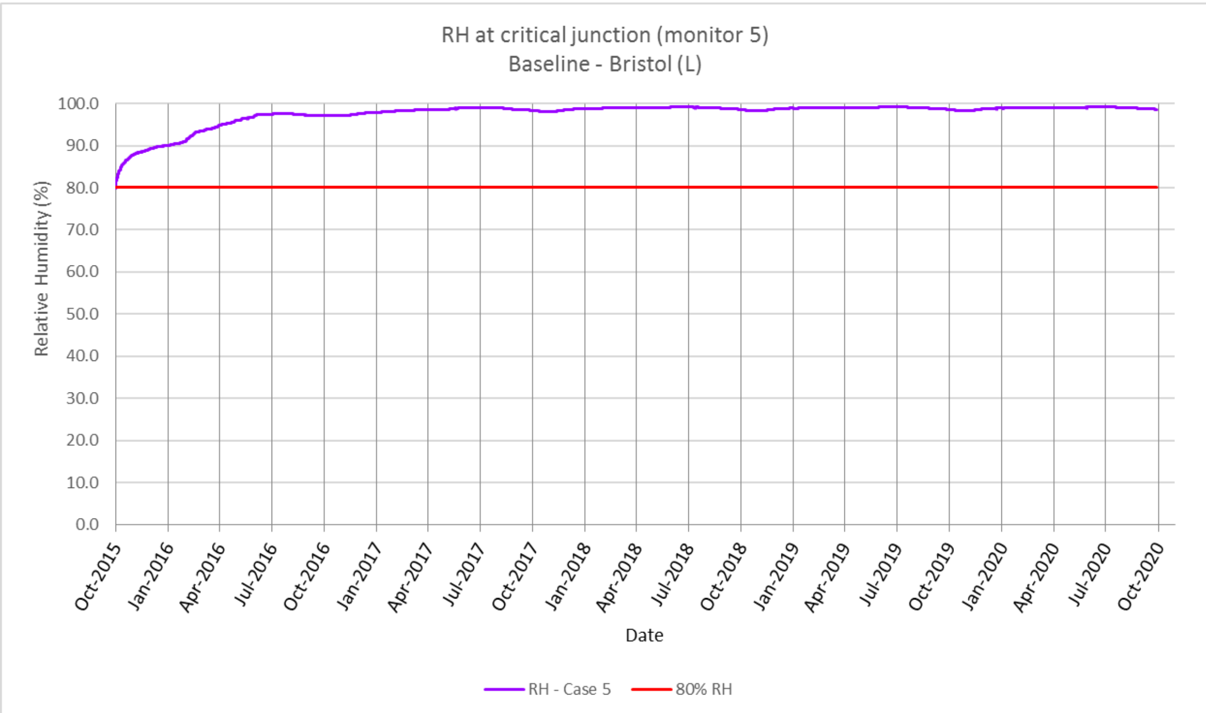


Figure 59: RH levels at critical junction for Case 5

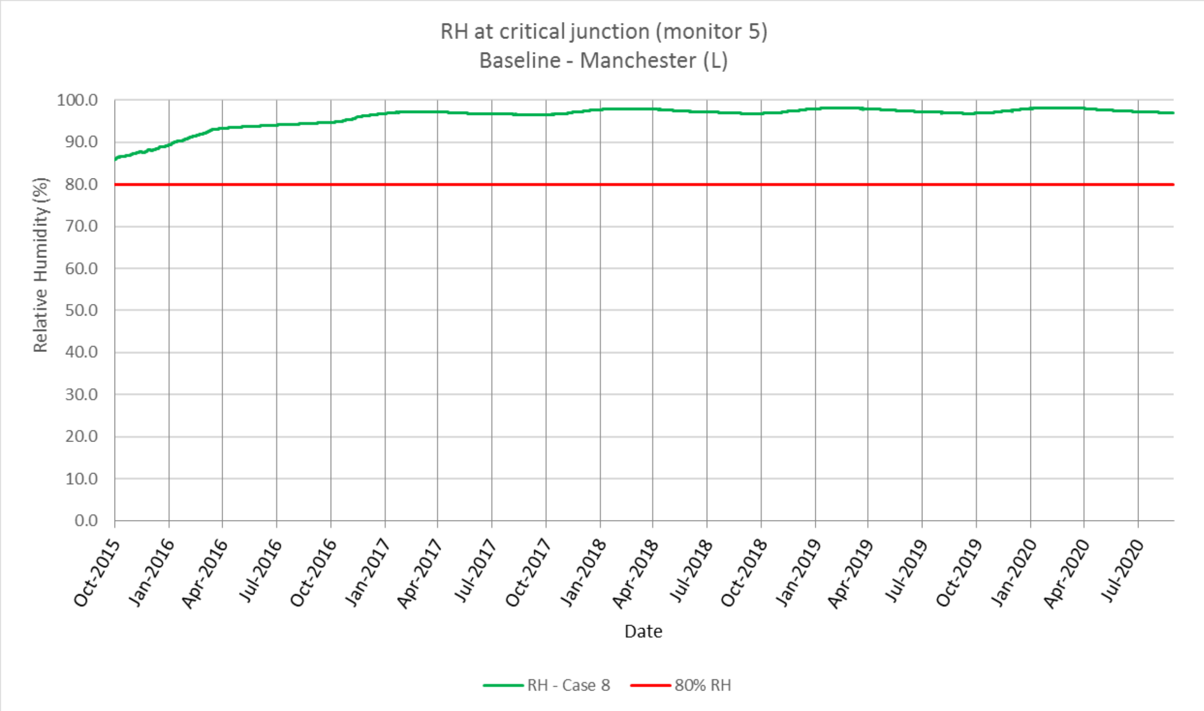


Figure 60: RH levels at critical junction for Case 8

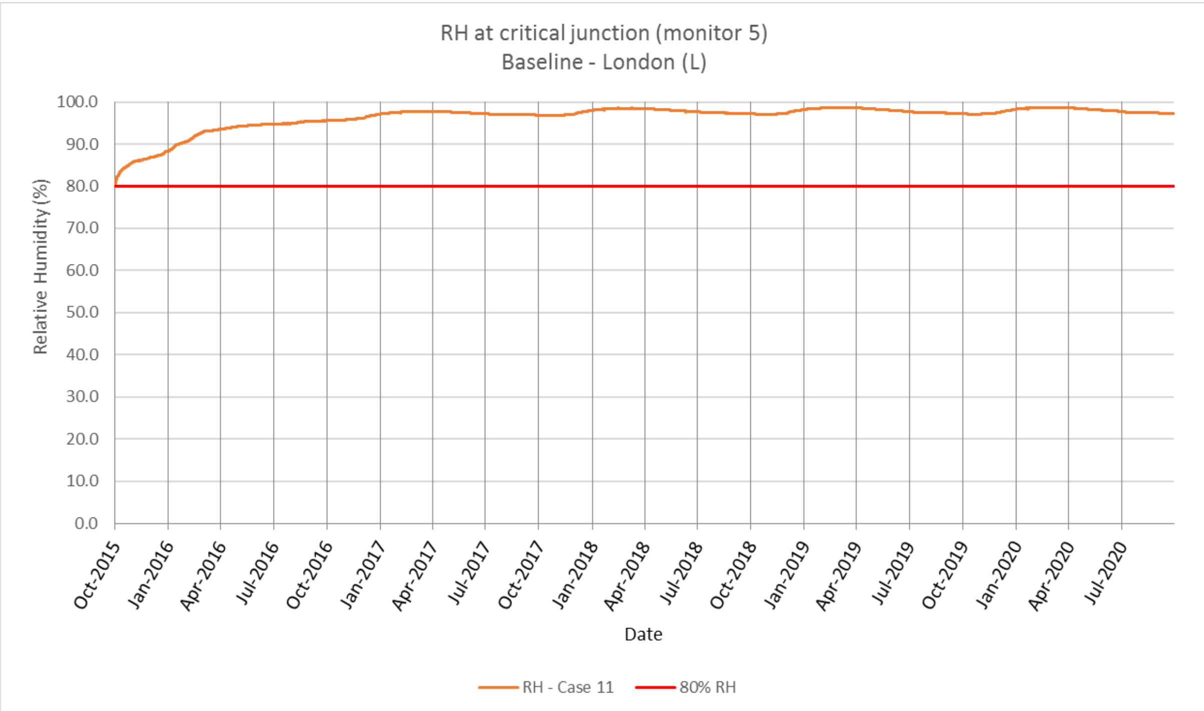


Figure 61: RH levels at critical junction for Case 11

15.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>

All scenarios achieve equilibrium. However, all scenarios display RH levels well above 80%. 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. The other cases also display extremely high RH levels, maintained throughout the year above 95%.

Even if the cases in the more protected zones do not show the occurrence of interstitial condensation, the extremely high RH levels show a high risk of mould growth. Indeed, one of the materials present at the critical junction is lime plaster, being an organic material and being considered food for mould growth. In addition, temperatures in summer at the junction are warm enough to support mould growth, and it is unlikely for retrofitted walls to be perfectly flat and air not to be present in some places at this junction. Therefore, these graphs show that, even if interstitial condensation might not happen in all cases, there is a significant risk for mould growth at this interface.

All scenarios are therefore considered a ‘fail’. These results are summarised in the table below.

Results

Table 19: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Fail	Case 5 Fail	Case 8 Fail	Case 11 Fail
Other	-	-	-	-

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 a closed-cell 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.

It is worth noting that the results are worse than for the new build internal insulated concrete wall (N8), which has a build-up with similar layers with the only difference being the solid wall brick material being replaced by concrete. This is due to the brick material being a higher absorbance material used to represent older solid brick walls typically present in older buildings, compared to the less absorbent moisture characteristics of concrete.

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.

15.3.5. 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.

15.4. Sensitivity Analysis – Change in Material [Cases X.d]: Change in Brick Physical Characteristics

15.4.1. Brick Physical Characteristics

This typology includes a porous material (the outer brick layer) being exposed to wind-driven rain and solar gains. The transient modelling of other typologies (N8 – solid concrete wall with IWI) indicates that the physical characteristics of the brick play a significant role on the hygrothermal performance of the build-up. Therefore, the first sensitivity analysis is carried out with a change in the brick physical characteristics, where two additional bricks are tested in addition to the brick used in the baseline model.

- Baseline Brick: Hand-formed brick (high absorption)

As explained in section 15.2.3, the default brick chosen for the baseline model is considered to be a conservative choice, due to the poor performance of the brick (porosity, water absorption coefficient). This brick can be described as a ‘high-absorption’ brick. This conservative approach is taken because of a lack of available data for UK building materials.
To assess the impact of brick characteristics onto the hygrothermal performance of this typology, two additional bricks (considered lower absorption) were chosen as alternatives for the first sensitivity analysis. Below is a short summary of their characteristics (see Appendix A for full material properties):

- Sensitivity 1: Solid Brick Masonry

The first lower absorption brick is chosen with a similar density and porosity to the default brick, while having a lower water absorption coefficient (0.110 $kg/m^2\sqrt{s}$ instead of 0.300$kg/m^2\sqrt{s}$).

- Sensitivity 2: Aerated Clay Brick (650 kg/m^3)

The second lower absorbent brick was chosen with much lower density (linked to a higher porosity) compared to the two previous bricks, and has a mid-range A-value of 0.097 kg/m²√s.

15.4.2. Sensitivity Analysis Cases

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the target U-value (as per baseline cases), for each of the two bricks tested in this sensitivity analysis:

Table 20: 4 sensitivity cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1.d	Case 4.d	Case 7.d	Case 10.d
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
Other	-	-	-	-

15.4.3. Graphs at Critical Junction

All graphs 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.

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). The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

As the bricks tested in this sensitivity analysis did not achieve equilibrium within the 5-year modelling period, the modelling period has been increased to 10 years to ensure equilibrium is reached in all cases.

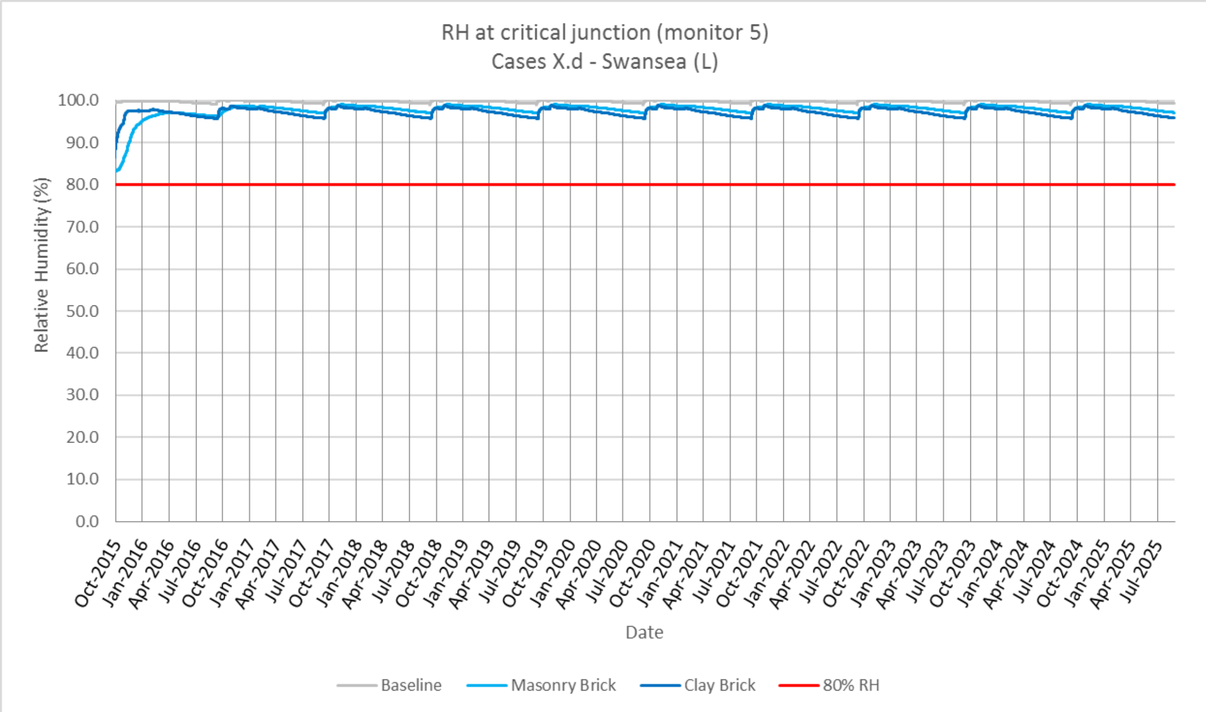


Figure 62: RH levels at critical junction for Cases 2 and 2.d for both brick types

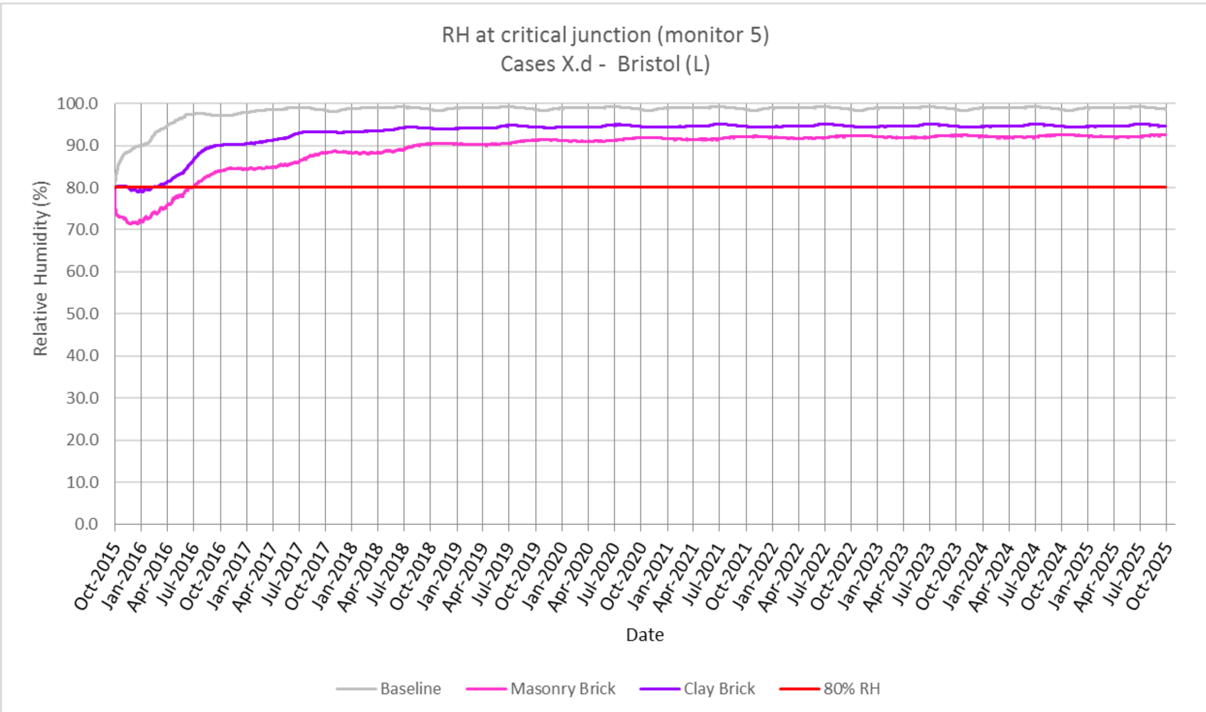


Figure 63: RH levels at critical junction for Cases 5 and 5.d for both brick types

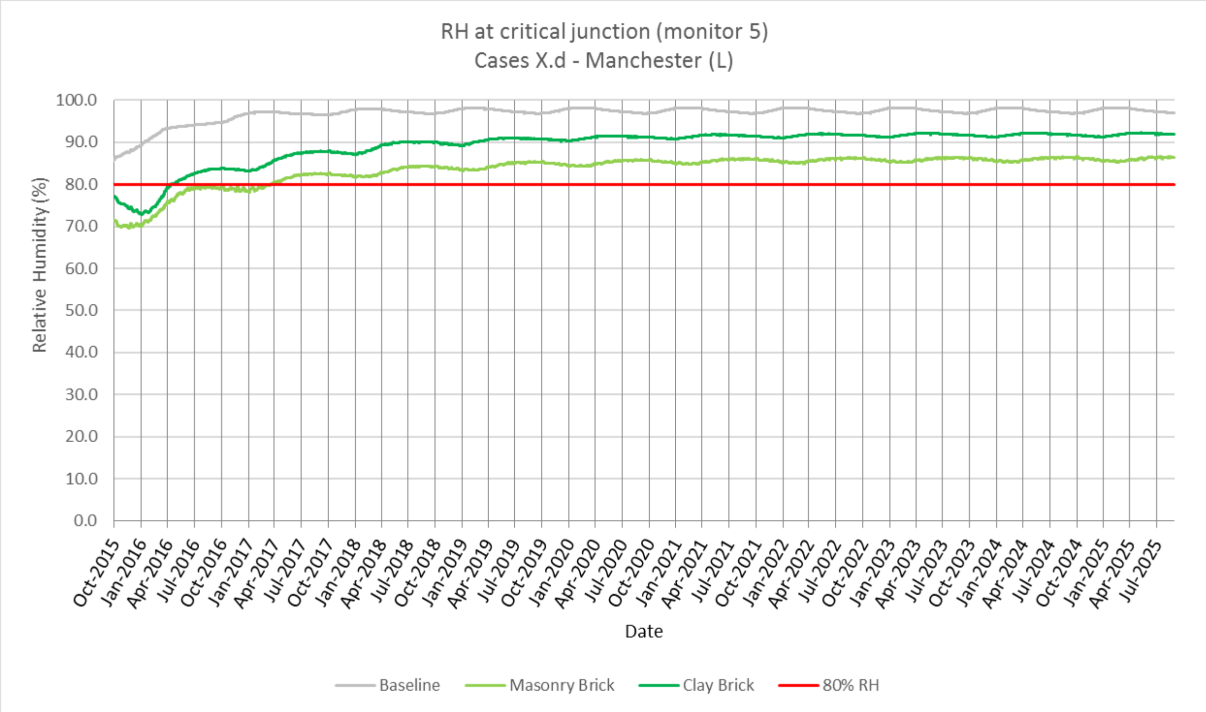


Figure 64: RH levels at critical junction for Cases 8 and 8.d for both brick types

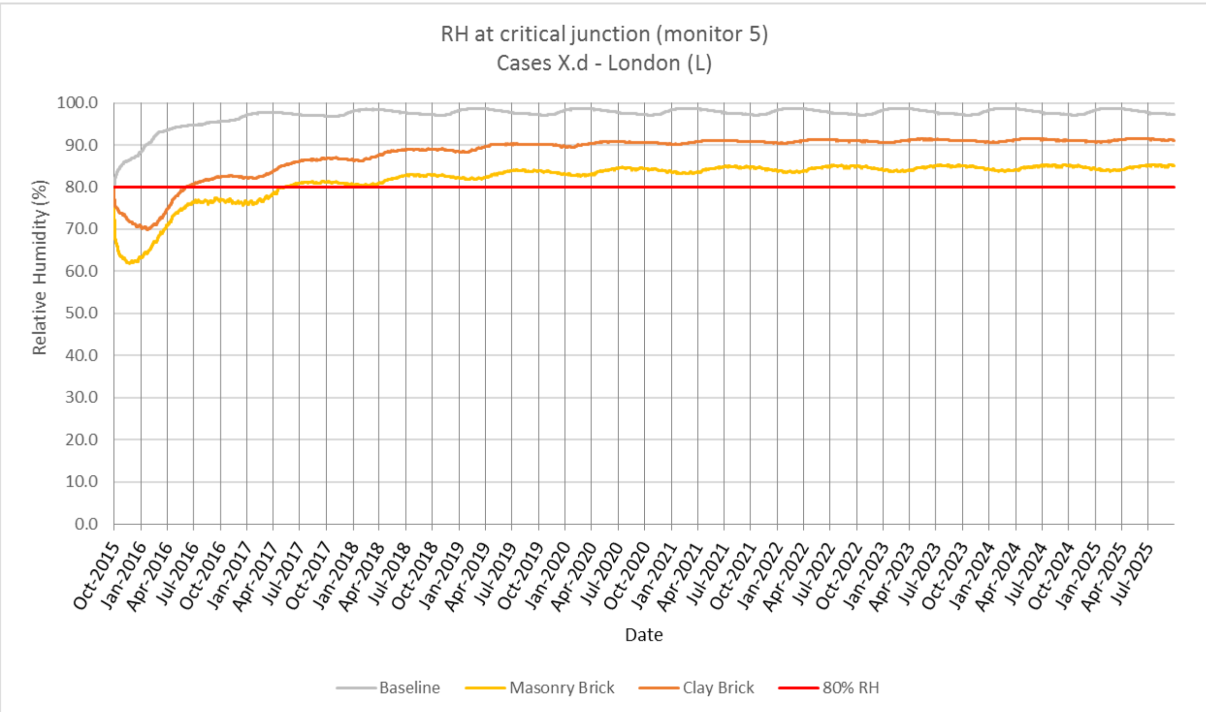


Figure 65: RH levels at critical junction for Cases 11 and 11.d for both brick types

15.4.4. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The graphs show that all cases modelled in this sensitivity analysis perform better than the baseline cases, as the RH profiles at the critical junction in the sensitivity analysis are kept consistently lower compared to their respective baseline.

However, this improvement in the hygrothermal performance of the build-up is not significant enough to change the status of the modelled cases, as RH levels at the critical junction still stay above the 80% RH threshold throughout 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.

Results
The table below summarises the performance of the modelled cases (for both types of bricks modelled in the sensitivity analysis):

Table 21: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	-	-	-	-
Part L	Case 2.d Fail	Case 5.d Fail	Case 8.d Fail	Case 11.d Fail
Other	-	-	-	-

Effects of Brick Physical Properties

Both sensitivity analysis bricks have very similar water absorption coefficient, called 'A-value', which is about three times lower than the brick used in the baseline cases. Therefore, it seems that the A-value is one of the key characteristics of the brick which has a direct and key impact on the hygrothermal performance of the build-up: the lower the brick A-value, the more resistant to moisture the build-up is.

The graphs show that both bricks give similar RH profile results, despite some of their characteristics being different. The small difference between the two sensitivity analysis bricks is likely to be explained by the difference in porosity. Indeed, the second brick (aerated clay brick) is about three times more porous than the first brick tested in the sensitivity cases (masonry brick) and a higher porosity means that there is more 'space' (holes) leading to a more important water ingress. Therefore, it seems that a lower porosity (normally linked to a higher density) can also improve the hygrothermal performance.

However, this overall improvement is not significant enough to improve the build-up's cases status from 'fail' to 'pass'. These results show that this build-up remains a risky build-up and is prone to permanent high RH levels at the critical junction, which could lead to mould growth and/or a reduction in thermal performance.

15.5. Sensitivity Analysis – Change in Orientation [Cases X.c]: North-facing walls

15.5.1. Sensitivity Analysis Cases

As the build-up is exposed to the wind-driven rain, which has a significant impact on its hygrothermal performance, the second sensitivity analysis is to change the orientation of the façade. With this sensitivity analysis, the orientation of the façade is changed from South-West to North.

A build-up on a South-West facing orientation experiences more extreme levels of wind-driven rain (being detrimental to the hygrothermal performance of the build-up) but benefits from greater solar gains (allowing it to dry out quicker). In comparison, a build-up on a North facing orientation experiences less wind-driven rain, but the lack of solar gains leads to a reduction in drying capabilities.

The overall impact of the change of orientation is difficult to predict, as it is the balance between the (beneficial) reduction in wind-driven rain and the (detrimental) reduction in solar gains that will inform the change in hygrothermal performance of the build-up.

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the Part L target U-value (as per baseline cases):

Table 22: 4 sensitivity cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1.c	Case 4.c	Case 7.c	Case 10.c
Part L	Case 2.c	Case 5.c	Case 8.c	Case 11.c
Other		-	-	-

15.5.2. Graphs at Critical Junction

All graphs 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.

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). The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

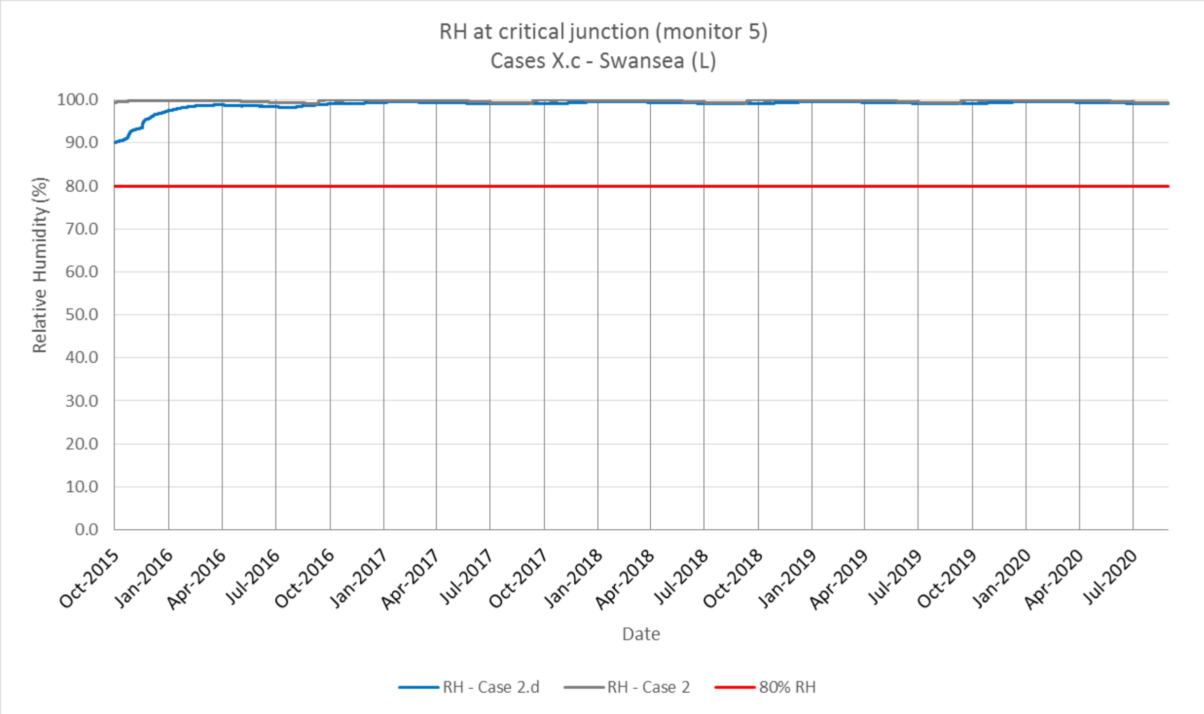


Figure 66: RH levels at critical junction for Cases 2 and 2.c

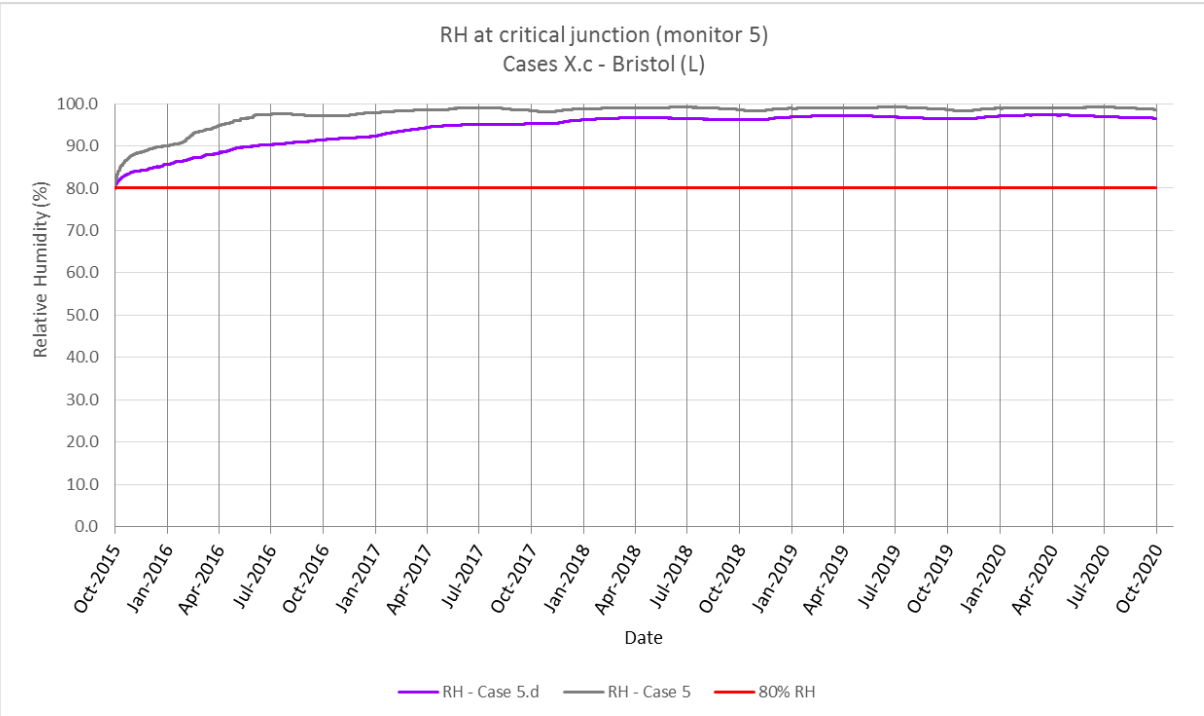


Figure 67: RH levels at critical junction for Cases 5 and 5.c

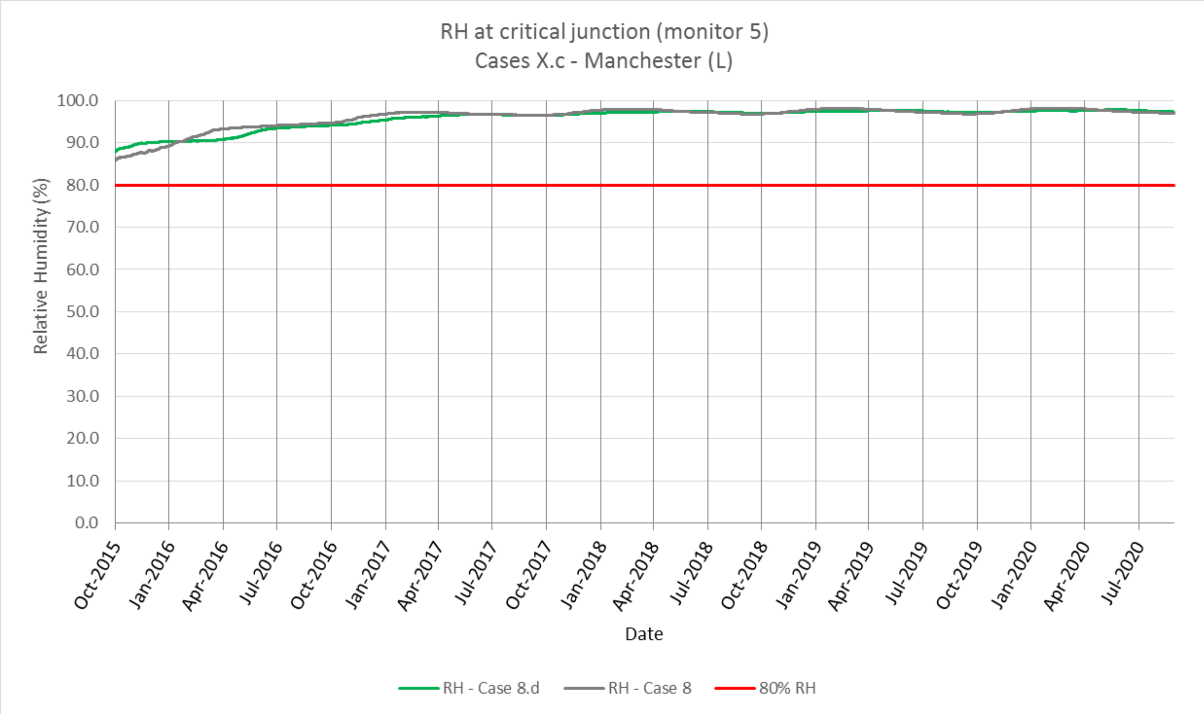


Figure 68: RH levels at critical junction for Cases 8 and 8.c

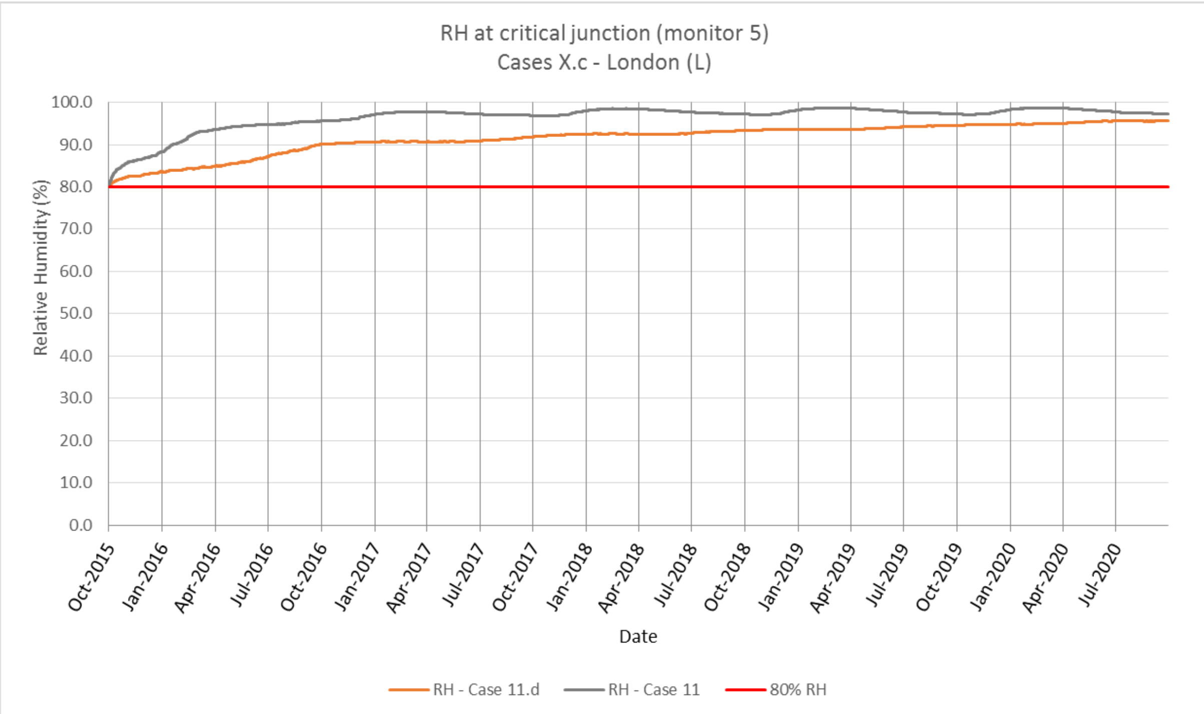


Figure 69: RH levels at critical junction for Cases 11 and 11.c

15.5.3. Conclusions – Sensitivity Analysis Cases X.c

Moisture risk assessment criteria

The graphs show that all cases modelled in this sensitivity analysis perform either identical or slightly better than their respective baseline cases. However, this improvement is small and is not sufficient enough to change the status of these cases – they are still all considered as 'fail'. Indeed, all cases display RH levels higher than 80% at the critical junction throughout the entire year.

Effects of exposure zones

The graphs show that, in the most extreme exposure zone (Zone 4 – Swansea) and the coldest zone (Zone 2 – Manchester), the impact of the change in orientation is negligible. Indeed, the RH profiles between the baseline and the sensitivity cases at the critical junction are almost identical. The results for Zone 4 (Swansea) might be due to the fact that the wind-driven rain can be considered very extreme in 'absolute' terms on all orientations.

A small beneficial effect is more visible in less extreme and warmer zones (Zone 1 – London and Zone 3 – Bristol). This beneficial effect is visible through the decrease in RH levels at the critical junction between the baseline and the sensitivity cases being maintained throughout the modelling period. This means that the reduction in wind-driven rain plays an overall more important role than the reduction in solar gains.

Impact of Brick Physical Properties

The sensitivity analysis is done on the baseline brick, which is a conservative assumption in terms of brick physical properties. The impact of the change in orientation is considered very small, as the high absorption of the chosen brick is still driving the poor performance of the build-up.

It is worth noting that, with a 'better' brick (such as the two additional bricks used in the sensitivity analysis cases), the beneficial impact of the change in orientation is considered more important than on the baseline brick. However, despite this improvement being better, it is still a not significant enough improvement to change the current results and the status of all the modelled cases.

Results
The table below summarises the performance of the sensitivity analysis cases:

Table 23: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	-	-	-	-
Part L	Case 2.c Fail	Case 5.c Fail	Case 8.c Fail	Case 11.c Fail
Other	-	-	-	-

These graphs show that, on average, the (beneficial) reduction in wind-driven rain and the (detrimental) reduction in solar gains have an overall small beneficial impact on the hygrothermal performance of the build-up. However, this improvement is small and not significant enough to improve the build-up's status from 'fail' to 'pass'.

Therefore, this build-up remains a risky build-up that is prone to high risks of mould growth and interstitial condensation, and therefore cannot be considered robust to resistance to moisture, regardless of the build-up's orientation (as well as the brick physical properties).

These results also highlight that a South-West orientation typically is the orientation which will display the worst hygrothermal performance, and should therefore be the one modelled / analysed if this build-up is considered at a design stage.

15.6. Sensitivity Analysis – Change in Material [Cases X.d]: Reduced insulation thickness

15.6.1. Sensitivity Analysis Cases

As the baseline build-up fails for all cases, due to the wind-driven rain penetrating through the external surface and reaching the critical junction kept at a cold temperature due to the addition of the IWI, an additional sensitivity analysis is to reduce the thickness of the internal insulation layer applied to the brickwork.

This is designed to increase the temperatures in the brick wall and at the critical junction, thus to reduce the corresponding relative humidity. This approach is recommended by some organisations to limit the impact of internal wall insulation retrofit on moisture issues in solid walls. The thickness of insulation is reduced from 78mm to 25mm (thinnest possible likely to be installed).

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones:

Table 24: 4 sensitivity cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	(baseline)	(baseline)	(baseline)	(baseline)
25mm Ins.	Case 2.d	Case 5.d	Case 8.d	Case 11.d
Other		-	-	-

15.6.2. Graphs at Critical Junction

All graphs 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.

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). The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

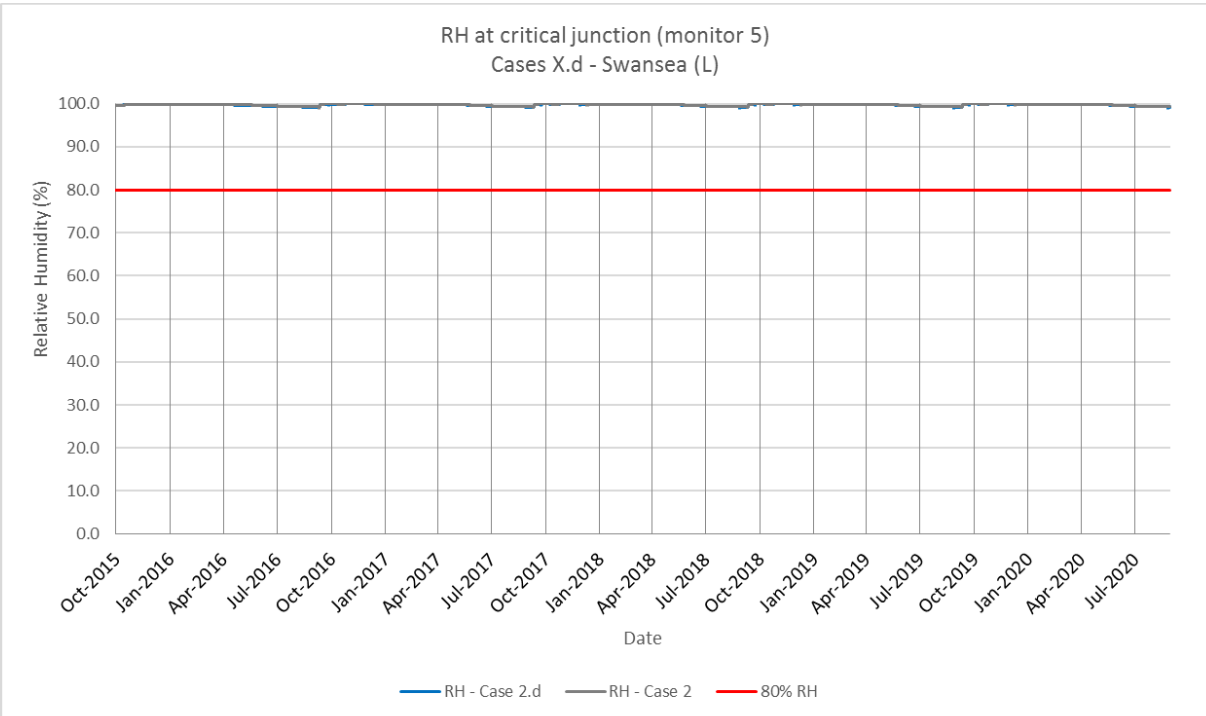


Figure 70: RH levels at critical junction for Cases 2 and 2.d

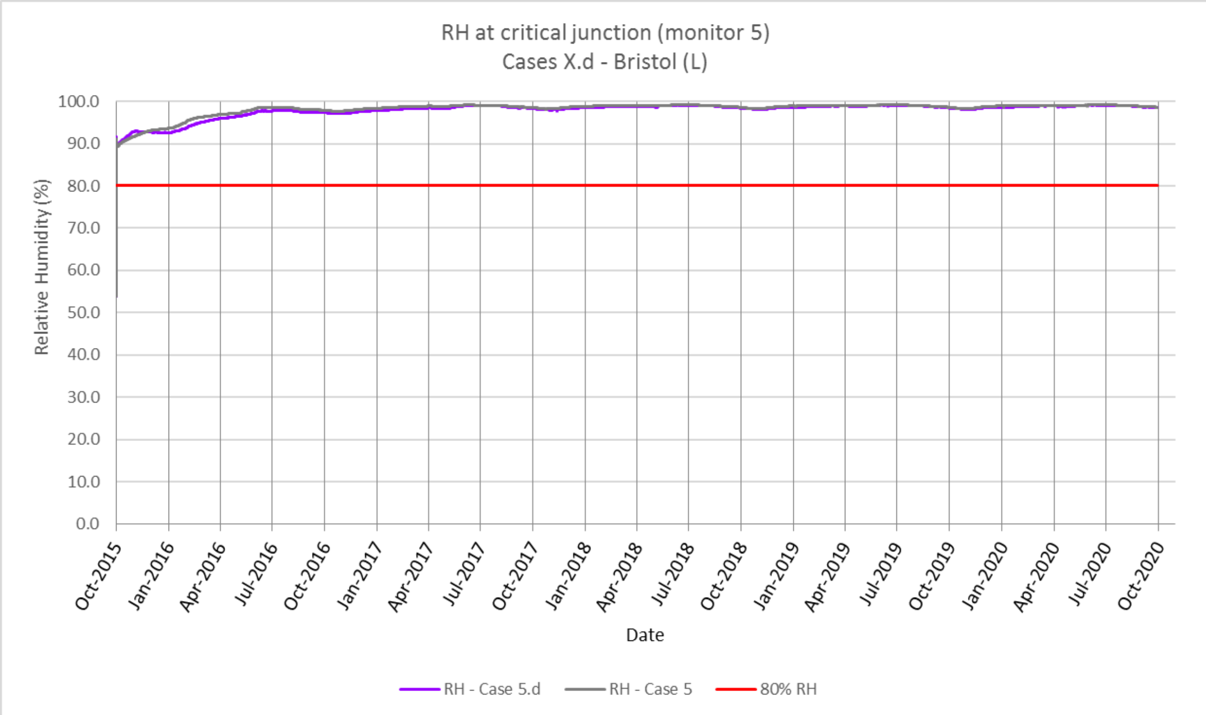


Figure 71: RH levels at critical junction for Cases 5 and 5.d

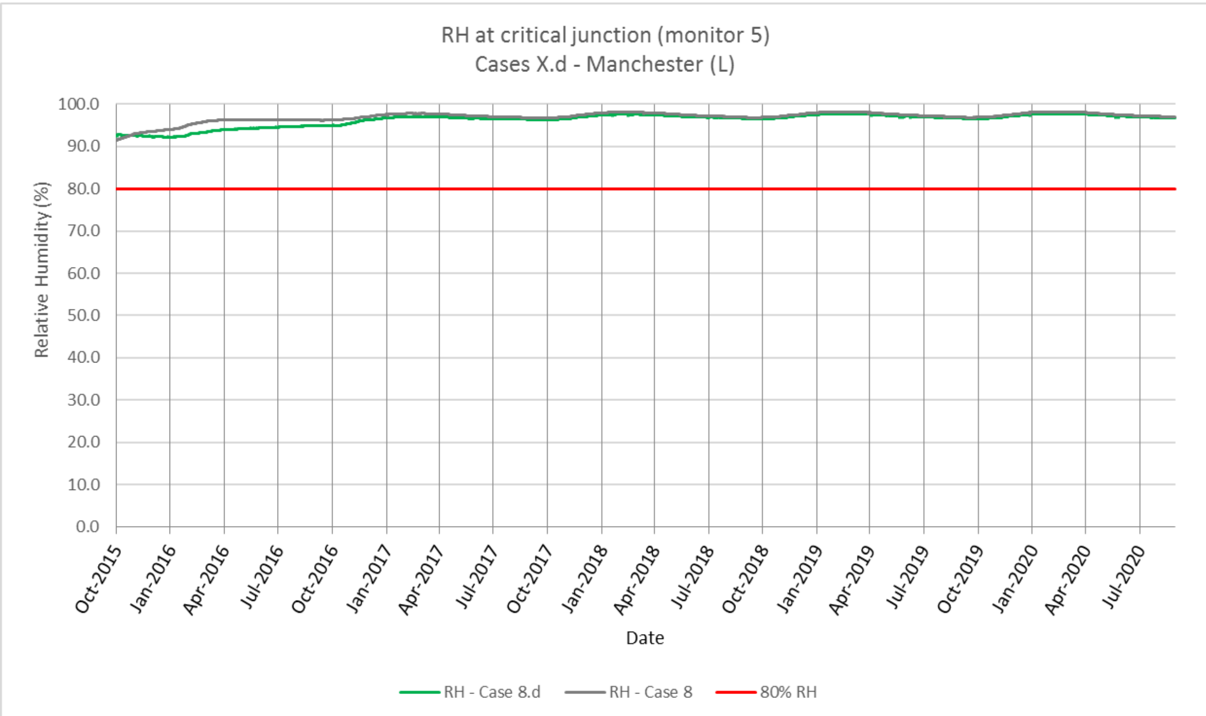


Figure 72: RH levels at critical junction for Cases 8 and 8.d

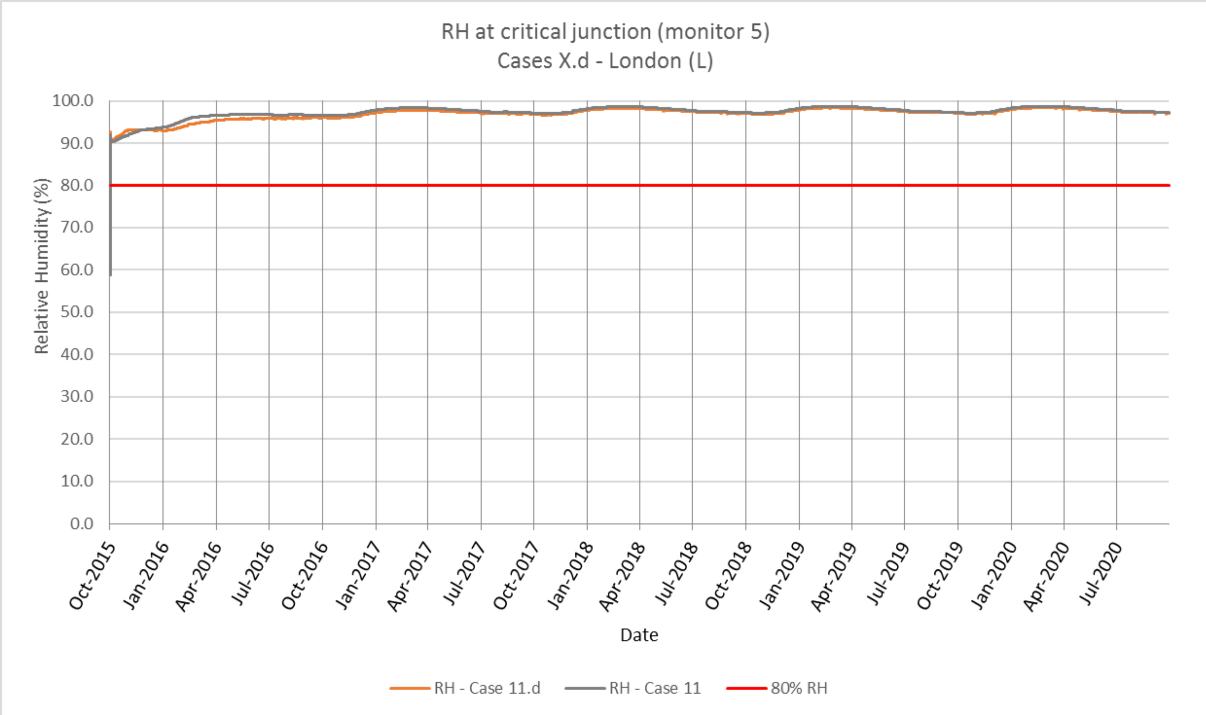


Figure 73: RH levels at critical junction for Cases 11 and 11.d

15.6.3. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The reduction in insulation has a negligible impact on the performance of the build-up. This is a smaller impact than was expected, as the critical junction is kept slightly warmer. As such all the cases continue to fail.

Results

The table below summarises the performance of the sensitivity analysis cases:

Table 25: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	-	-	-	-
Part L	Case 2.d Fail	Case 5.d Fail	Case 8.d Fail	Case 11.d Fail
Other	-	-	-	-

These graphs show that, with the use of closed-cell insulation installed internally on a solid brick wall, the insulation thickness does not play a significant role on the hygrothermal performance of the build-up.

15.7. Sensitivity Analysis – Change in Material [Cases X.d]: Insulating Wallpaper

15.7.1. Sensitivity Analysis Cases

As with the previous sensitivity (reduced insulation thickness), since the baseline build-up fails for all cases, due to the wind-driven rain penetrating through the external surface and reaching the critical junction kept at a cold temperature due to the addition of the IWI, an additional sensitivity analysis is to model 'insulating wallpaper' by further reducing the thickness of the internal insulation layer applied to the brickwork, substituting the insulation with a latex based insulation directly applied to the plaster substrate, and allowing a fibreglass final coating.

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, using 'insulating 10mm wallpaper'):

Table 26: 4 sensitivity cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	(baseline)	(baseline)	(baseline)	(baseline)
10mm Ins.	Case 2.d	Case 5.d	Case 8.d	Case 11.d
Other		-	-	-

15.7.2. Graphs at Critical Junction

All graphs 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.

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). The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

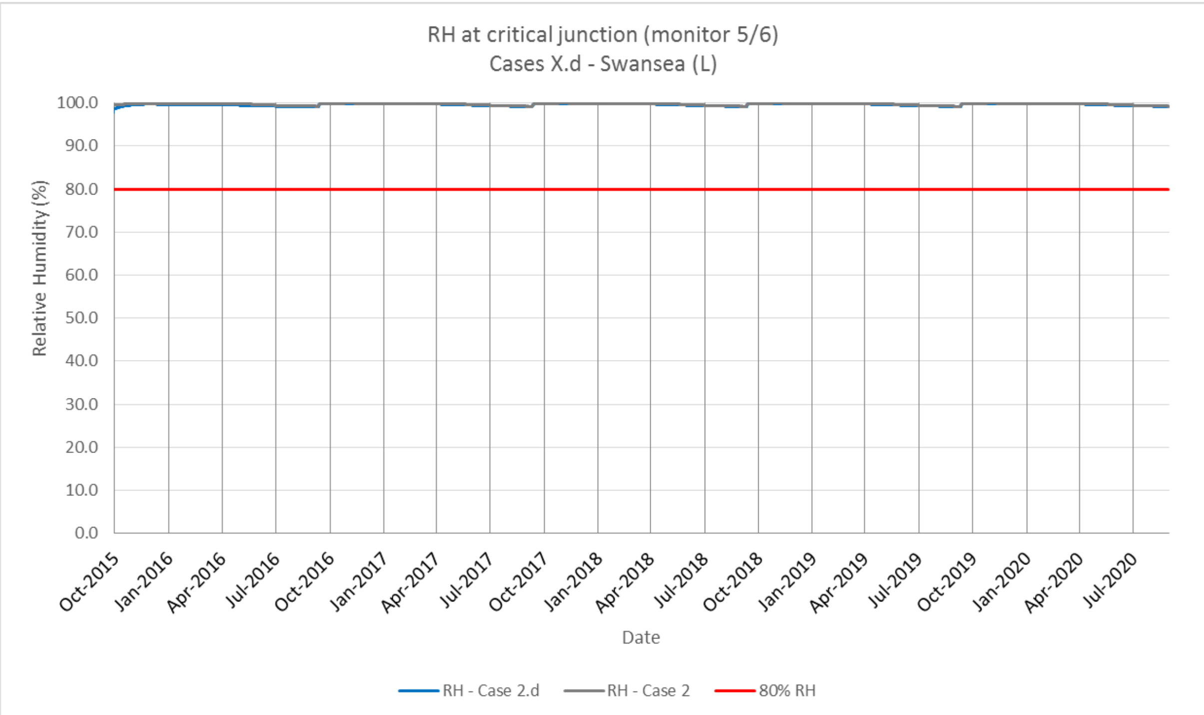


Figure 74: RH levels at critical junction for Cases 2 and 2.d

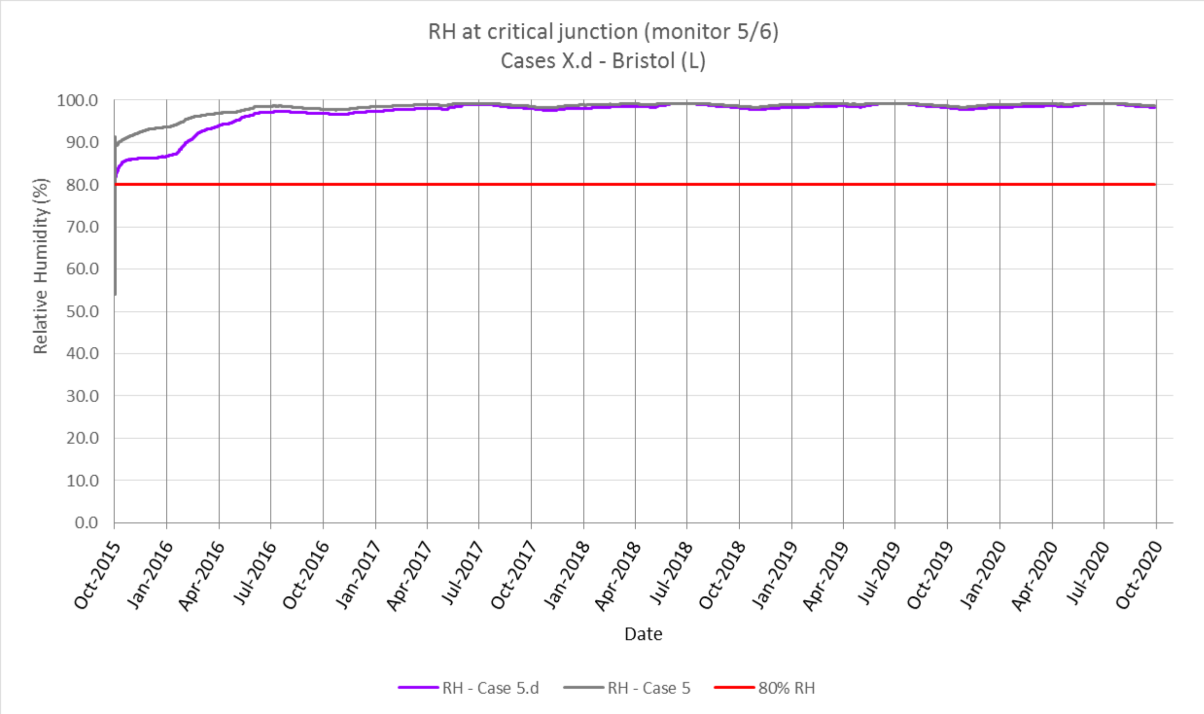


Figure 75: RH levels at critical junction for Cases 5 and 5.d

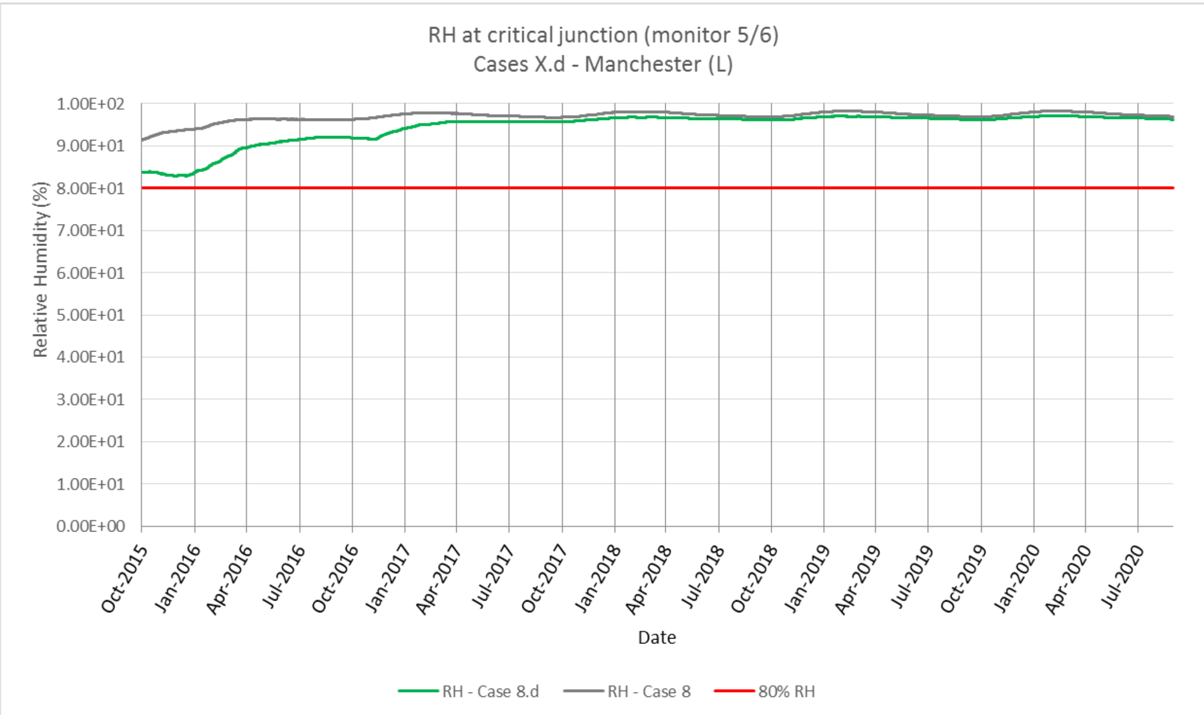


Figure 76: RH levels at critical junction for Cases 8 and 8.d

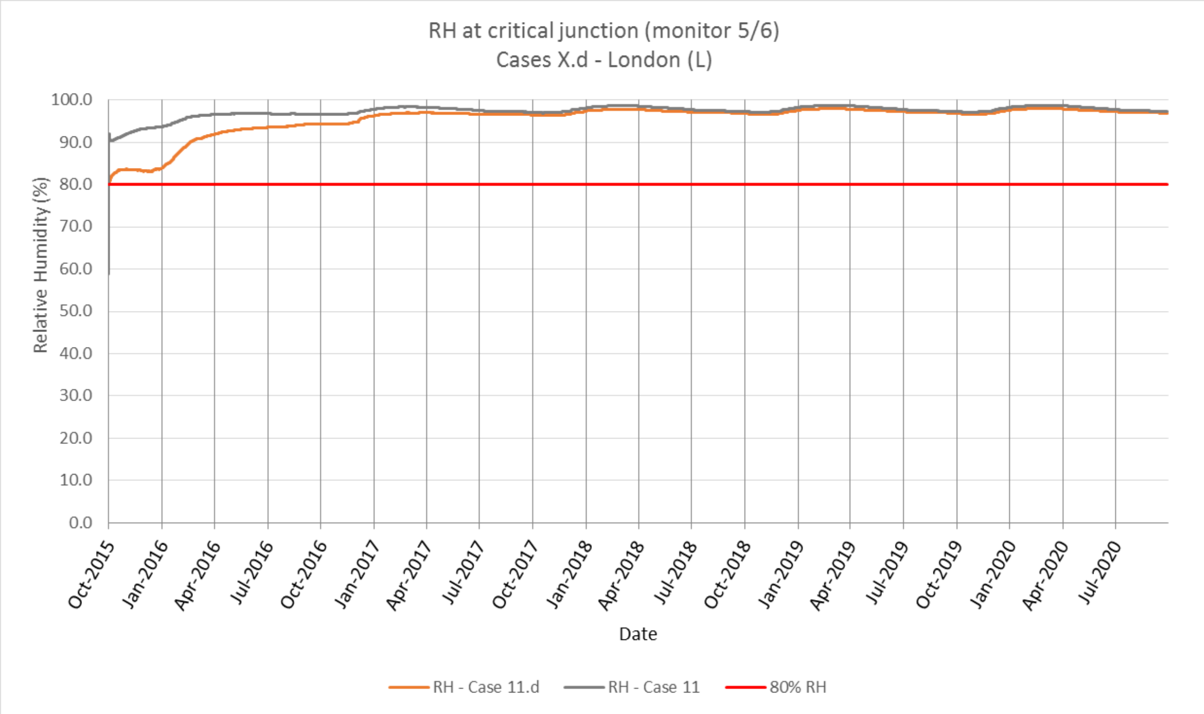


Figure 77: RH levels at critical junction for Cases 11 and 11.d

15.7.3. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The substitution of insulation type, reduction in thickness and removal of the air gap has a negligible overall impact on the performance of the build-up. As such all the cases continue to fail.

Results

The table below summarises the performance of the sensitivity analysis cases:

Table 27: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	-	-	-	-
Part L	Case 2.d Fail	Case 5.d Fail	Case 8.d Fail	Case 11.d Fail
Other	-	-	-	-

These graphs show that, with the use of latex insulation installed internally on a solid brick wall, the hygrothermal performance of the build-up continues to be most influenced by external moisture.

15.8. Sensitivity Analysis – Change in Material [Cases X.d]: Addition of a water-resistant external coating

15.8.1. Sensitivity Analysis Cases (higher absorption brick)

The baseline and both sensitivity analysis build-ups fail for all cases, mainly due to the wind-driven rain reaching the external surface and penetrating through the brick, being very porous materials. Therefore, the next sensitivity analysis is to improve the build-up's resistance to moisture by introducing a "brick cream" coating into the external layer of the brickwork. Per definition, this will reduce the amount of wind-driven rain penetrating the build-up and therefore should have a beneficial impact on its hygrothermal performance.

Brick creams (also called protection creams) are relatively new products and a very limited amount of testing has been performed on them. Due to these limitations, input data related to the brick cream have been taken from the 'Safeguard Stormdry masonry protection cream', as it appears this product is by far the main product used in the industry and seems to be the only (partially) tested yet.

The type of brick cream chosen is a water repellent cream for brick, is based on silane / siloxane (silicon) technology and works by lining the pores of the brick wall rather than blocking them – to allow the wall to keep 'breathing' (which means that the transfer of water vapour is not stopped).

Assumptions used for the brick cream characteristics have been taken from available test data. Please find below the summary of the brick cream characteristics.

<u>Brick Cream WUFI Input Data</u>

- 10mm brick cream penetration into the brick (so 10mm external layer modelled with different characteristics compared to the rest of the brick)
- Reduction in water absorption coefficient (A-value) by 95%
- Increase in water vapour diffusion resistance factor (μ) by 10%

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the Part L target U-value (as per baseline cases):

Table 28: 4 sensitivity cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	(baseline)	(baseline)	(baseline)	(baseline)
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
Other	-	-	-	-

15.8.2. Graphs at Critical Junction (higher absorption brick)

All graphs 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.

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). The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

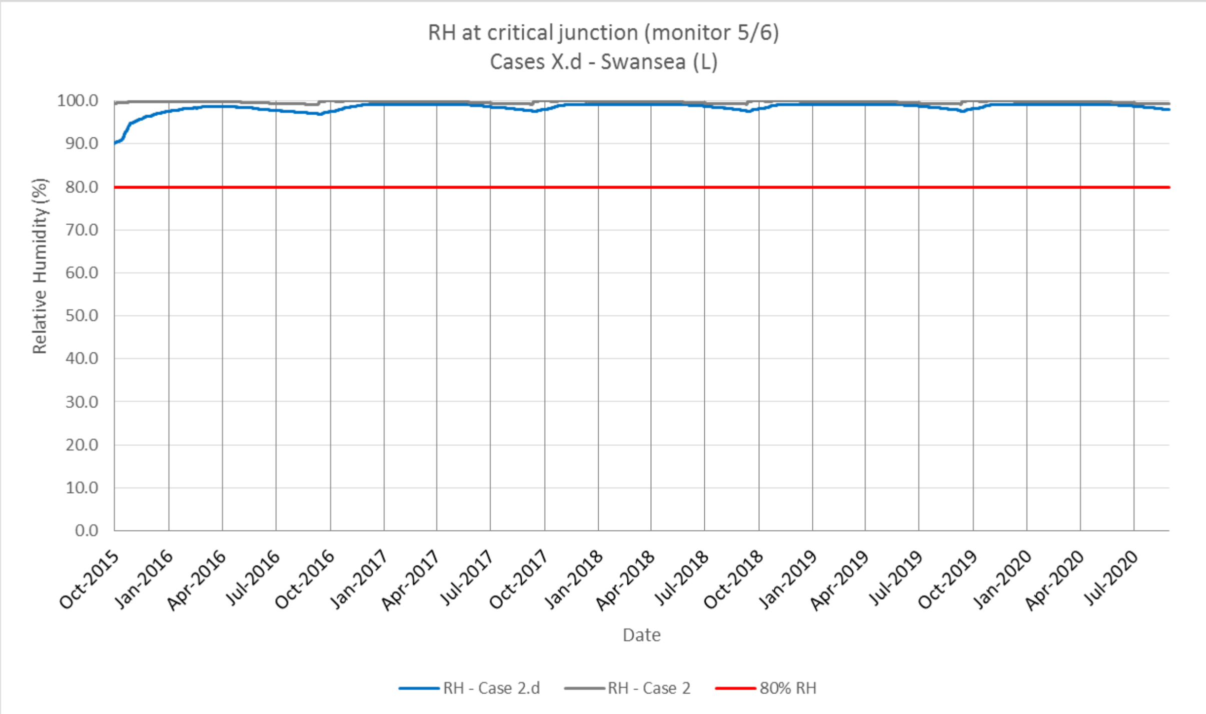


Figure 78: RH levels at critical junction for Cases 2 and 2.d

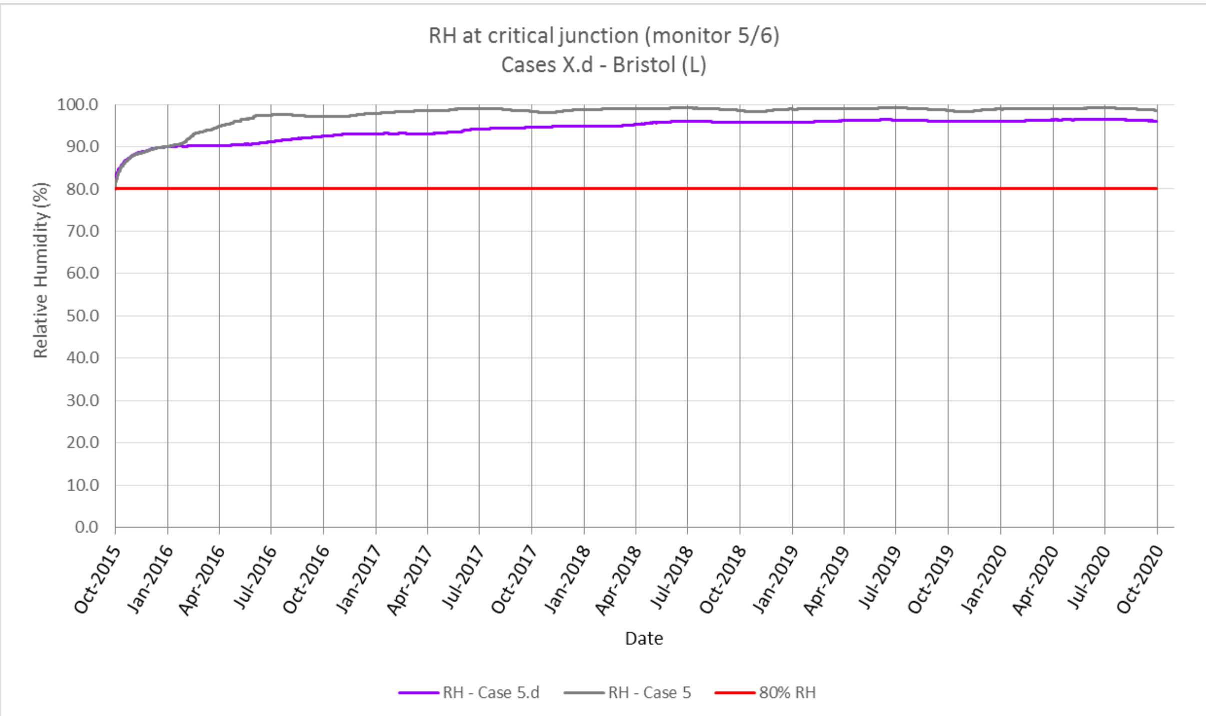


Figure 79: RH levels at critical junction for Cases 5 and 5.d

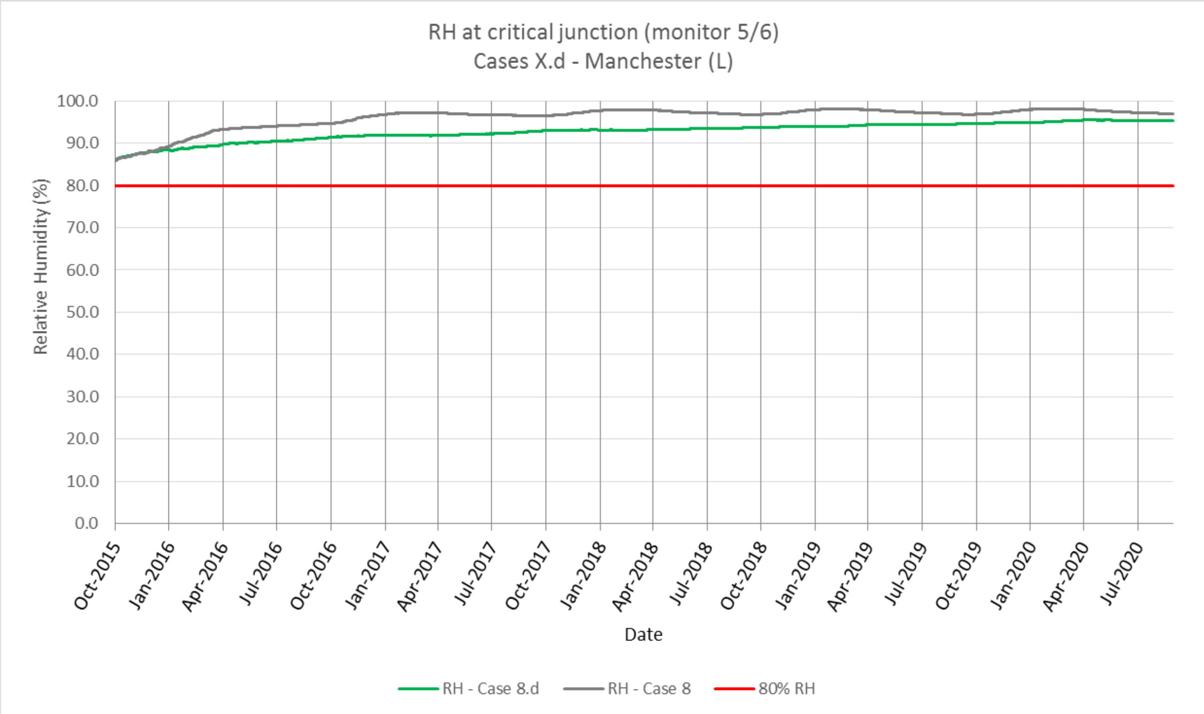


Figure 80: RH levels at critical junction for Cases 8 and 8.d

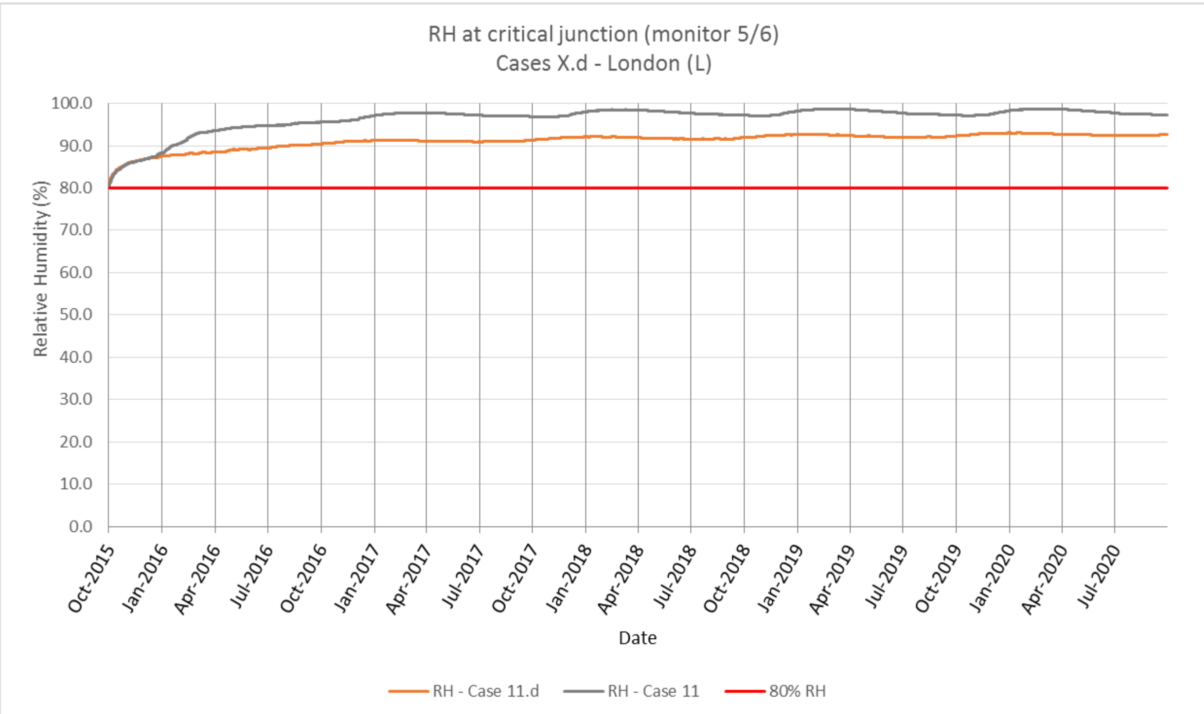


Figure 81: RH levels at critical junction for Cases 11 and 11.d

15.8.3. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The graphs show that all cases modelled in this sensitivity analysis perform better than their respective baseline cases.

All cases reach equilibrium. However, all cases still display RH levels much higher than the 80% RH threshold, which means that all cases remain a ‘fail’. Like previous sensitivity cases, the impact of measure tested (the use of the brick cream) is not significant enough to change the status of these cases.

Results

The table below summarises the performance of the sensitivity analysis cases:

Table 29: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	-	-	-	-
Part L	Case 2.d Fail	Case 5.d Fail	Case 8.d Fail	Case 11.d Fail
Other	-	-	-	-

These results show that the upgraded build-up with brick cream is made safer in terms of hygrothermal performance, compared to the baseline build-up. However, despite significantly improving its performance, this coating is not a sufficient enough solution to ensure the ‘safe’ performance of the build-up in these conditions (high absorption brick, south-west façade, with this specific build-up in terms of insulation thickness and material, etc.).

Water Content in Brick Layer

The wind-driven rain penetrating the brick is the main source of moisture which is leading to the failure of the build-up. Analysing the water content in this layer between the baseline and the sensitivity analysis case with brick cream is useful to quantify how much improvement is obtained through the installation of the brick cream.

The graph below displays the water content in the concrete layer for the case in Zone 4 (Swansea), as it is the most extreme case. As per other sensitivity modelling, the case X.d tested here is displayed as a coloured line against its respective baseline case, displayed with a grey line.

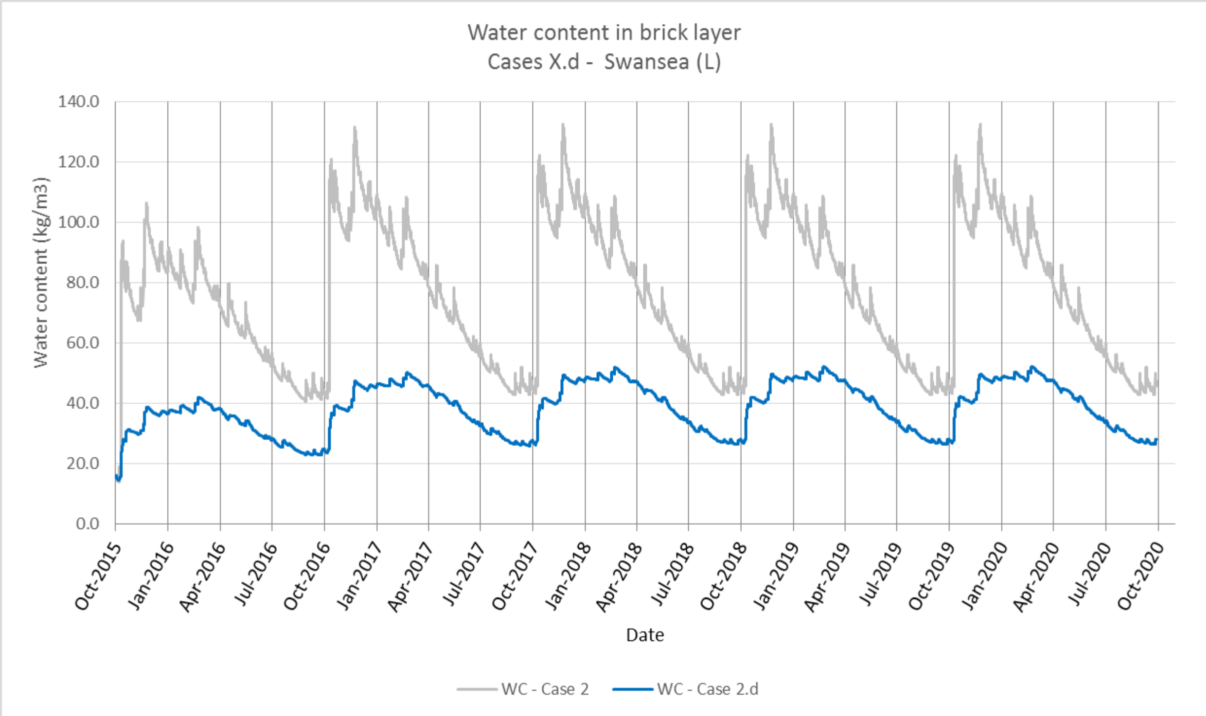


Figure 82: Water content in brick layer for Cases 2 and 2.d

The graph shows that the water content throughout the years in the brick layer is significantly reduced with the introduction of the brick cream, which explains the decrease in RH levels at the critical junction and therefore the improvement in the hygrothermal performance of the build-up.

Effects of exposure zones

The effects of exposure zones is visible on the graphs, with the beneficial impact of the application of the brick cream becoming increasingly visible the less exposed the zone in which the build-up is located.

Impact of Brick Physical Properties

The sensitivity analysis is done on the baseline brick, which is a conservative assumption in terms of brick physical properties. The impact of the addition of the brick cream is considered small, as the high absorption of the chosen brick is still driving the poor performance of the build-up.

It is worth noting that, with a 'better' brick (such as the two additional bricks used in the sensitivity analysis cases), it is likely for the beneficial impact due to the addition of the brick cream to be more significant. A further sensitivity analysis is therefore done in the following section to understand the impact of the brick cream on a lower absorption brick.

15.8.4. Sensitivity Analysis Cases (lower absorption brick)

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the Part L target U-value (as per baseline cases):

Table 30: 4 sensitivity cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	(first sensitivity)	(first sensitivity)	(first sensitivity)	(first sensitivity)
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
Other	-	-	-	-

15.8.5. Graphs at Critical Junction (lower absorption brick)

All graphs 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.

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). The sensitivity analysis cases (using the aerated clay brick, with the use of brick cream) are displayed as a coloured line, while their respective baseline cases (using the aerated clay brick, without the use of the brick cream) are displayed with a grey line.

- <u>Sensitivity 1: Solid Brick Masonry</u>

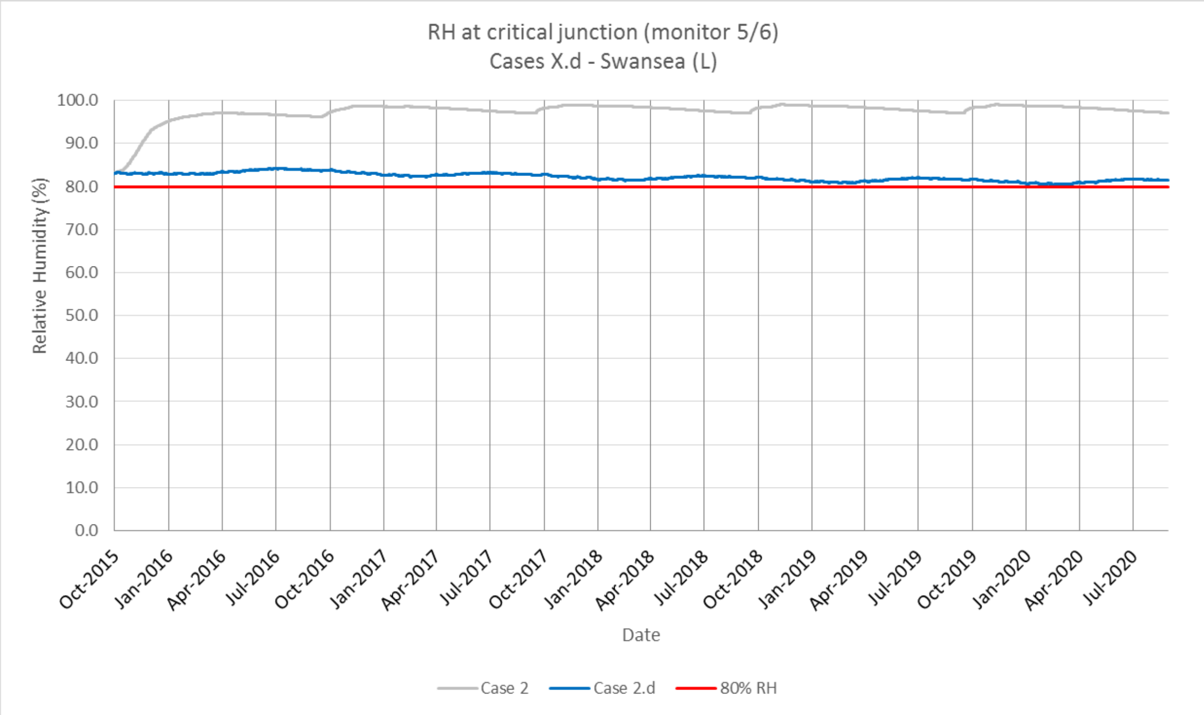


Figure 83: RH levels at critical junction for Cases 2 and 2.d (solid brick masonry)

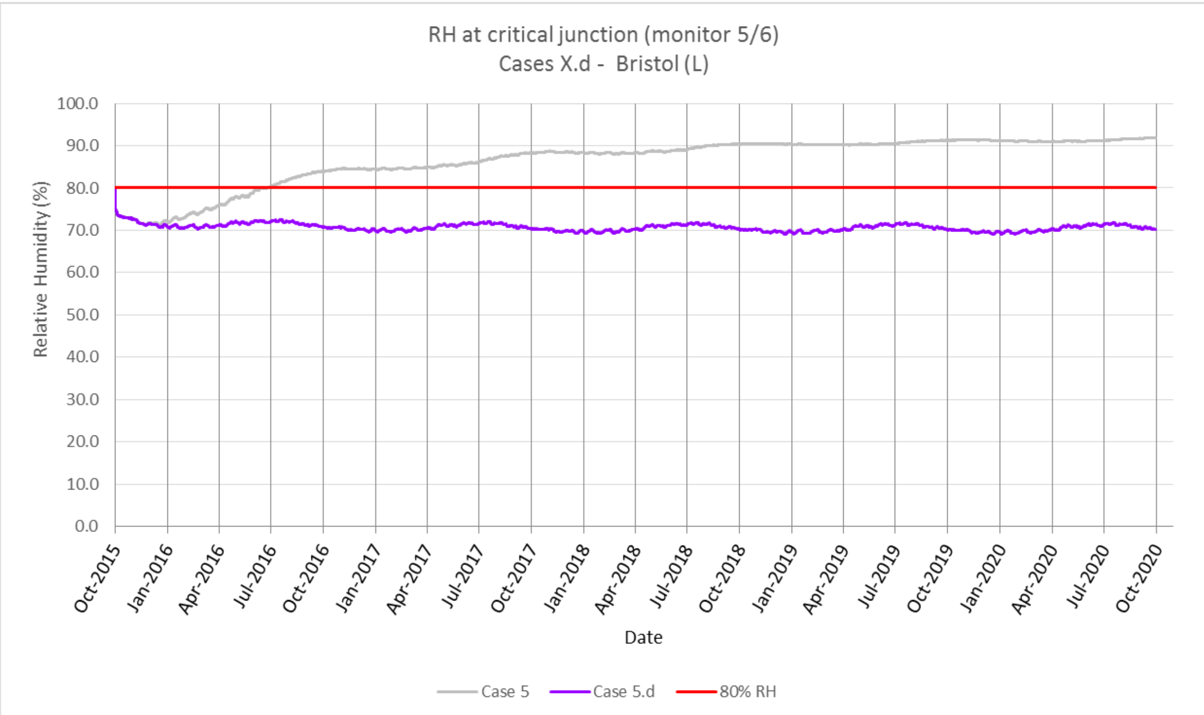


Figure 84: RH levels at critical junction for Cases 5 and 5.d (solid brick masonry)

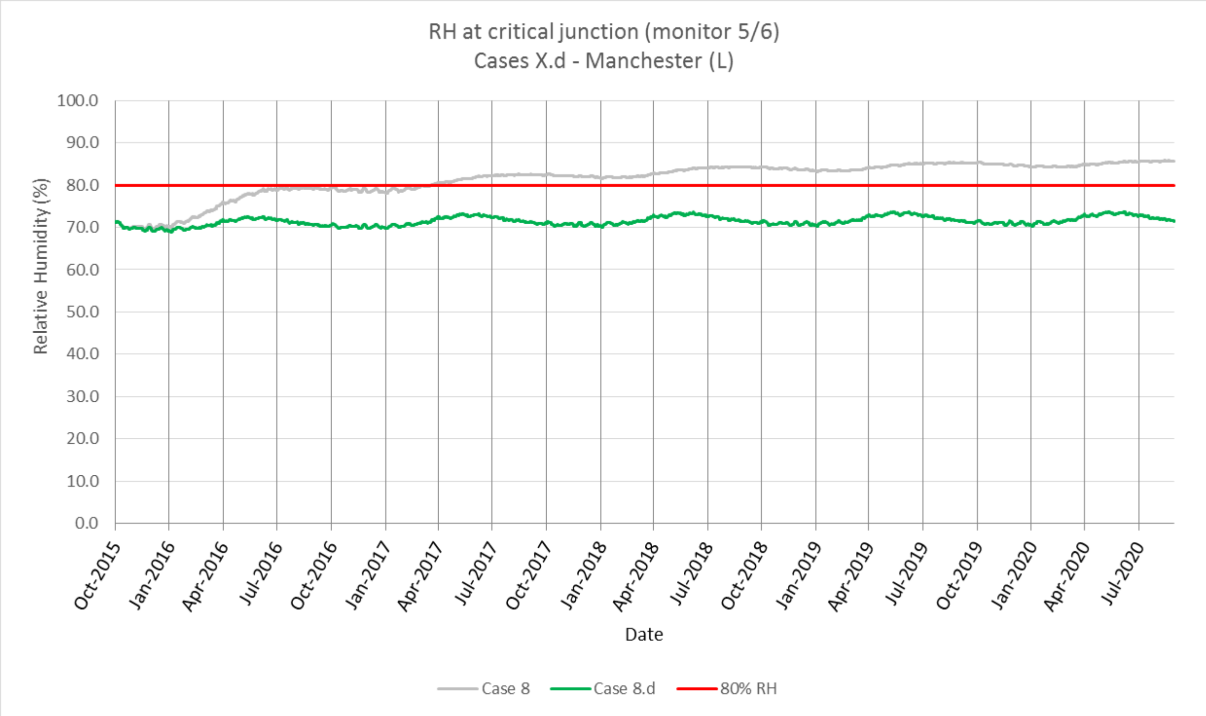


Figure 85: RH levels at critical junction for Cases 8 and 8.d (solid brick masonry)

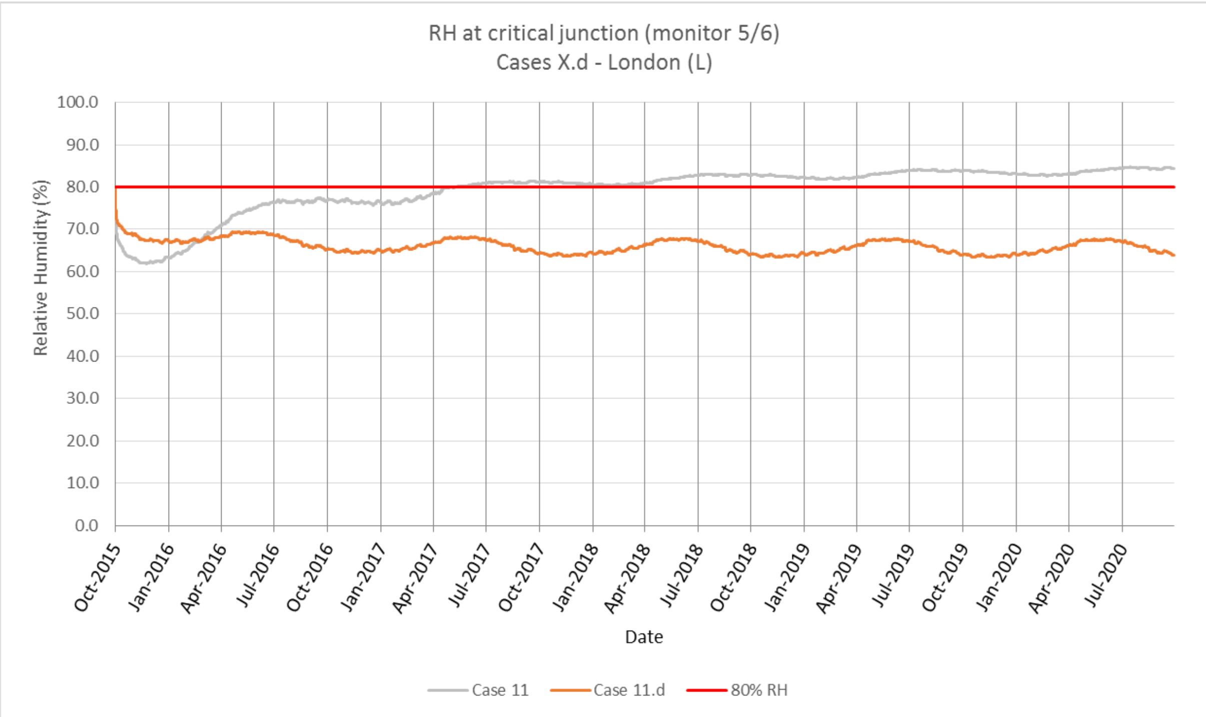


Figure 86: RH levels at critical junction for Cases 11 and 11.d (solid brick masonry)

- <u>Sensitivity 2: Aerated Clay Brick (650 kg/m3)</u>

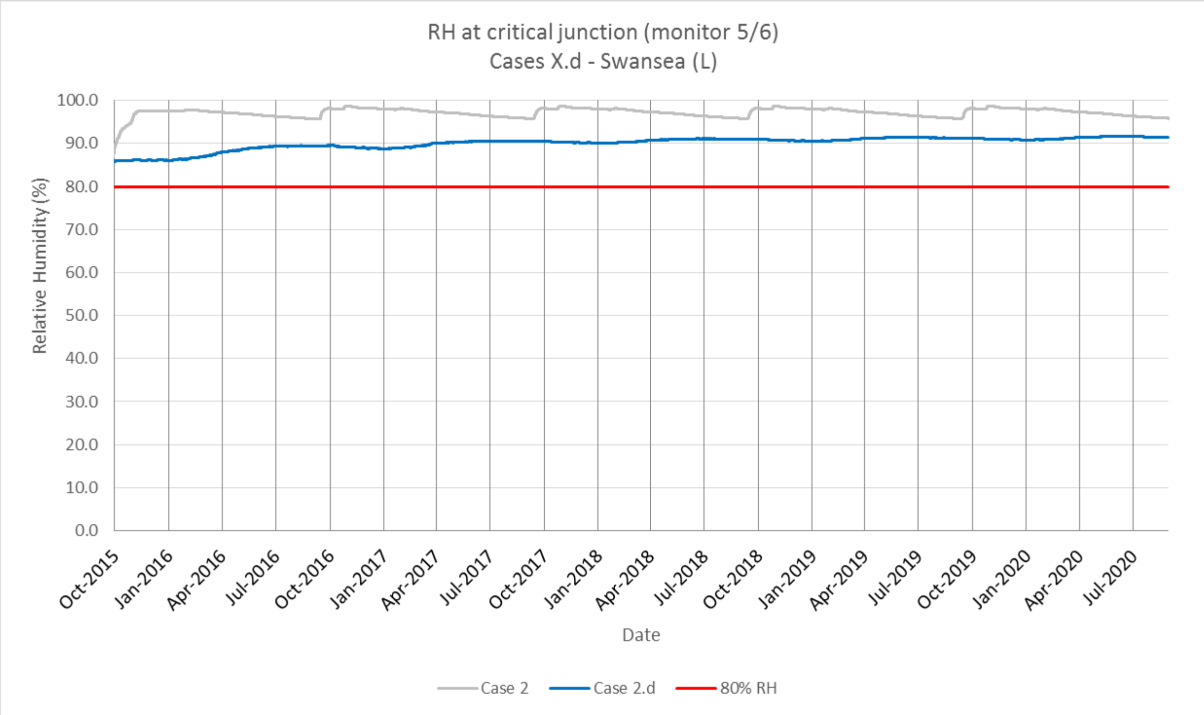


Figure 87: RH levels at critical junction for Cases 2 and 2.d (aerated clay brick)

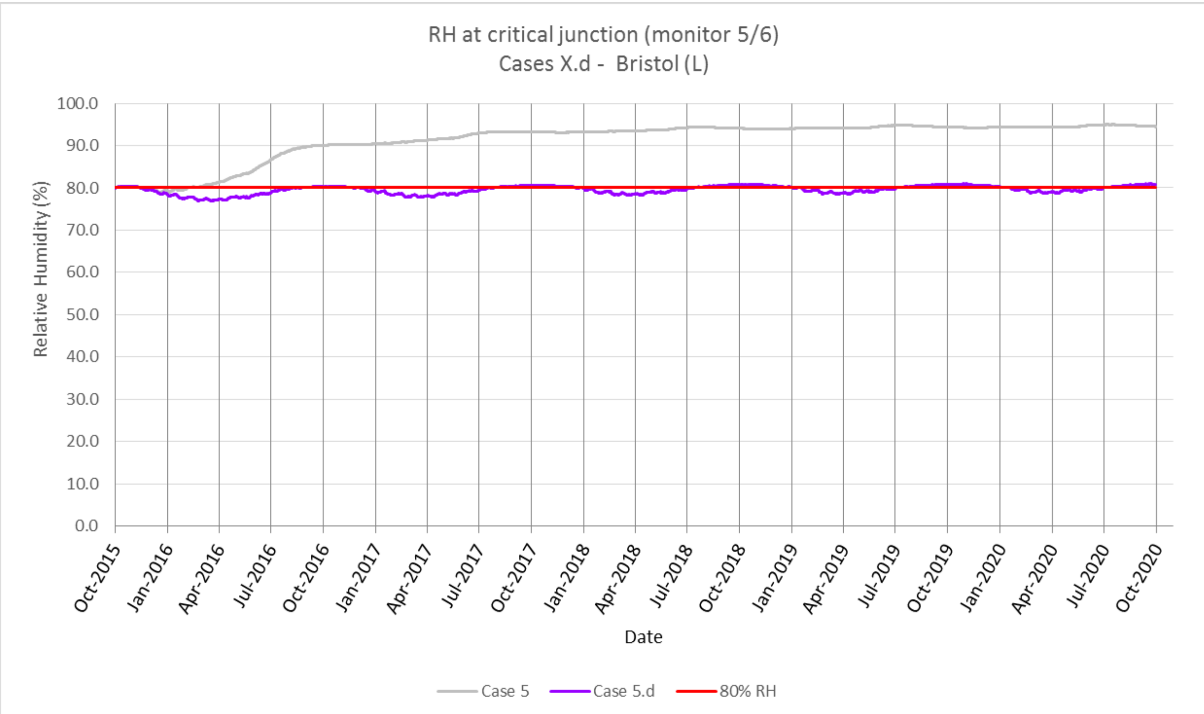


Figure 88: RH levels at critical junction for Cases 5 and 5.d (aerated clay brick)

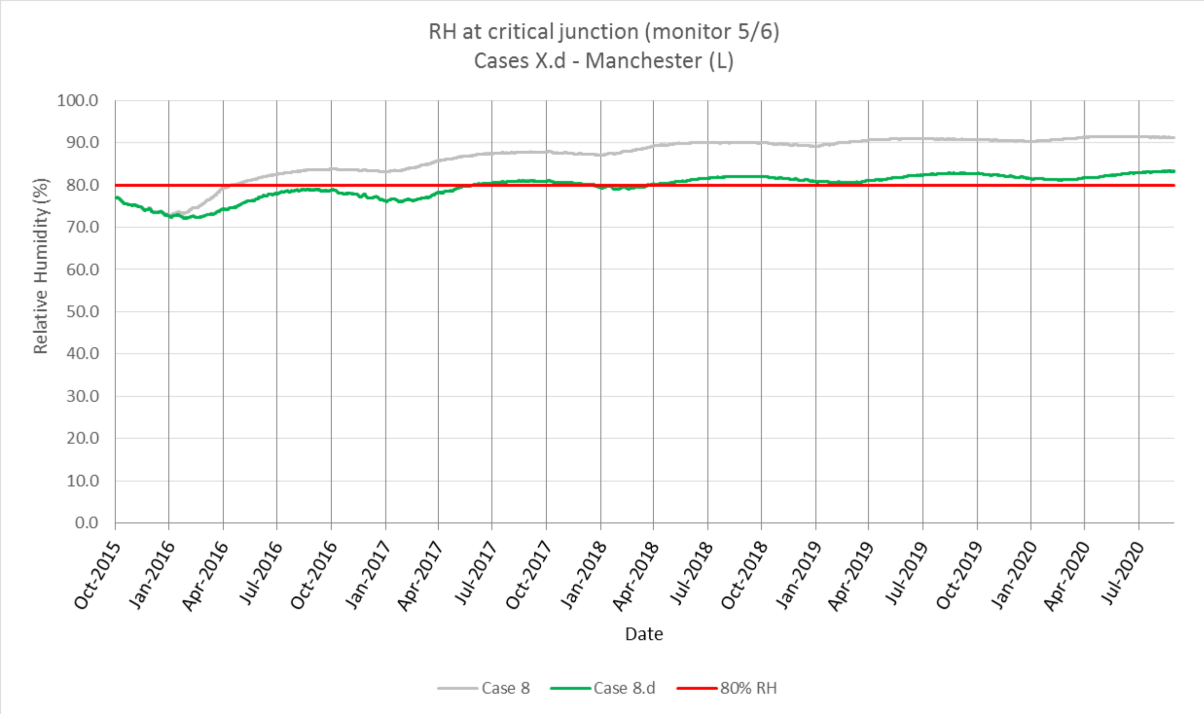


Figure 89: RH levels at critical junction for Cases 8 and 8.d (aerated clay brick)

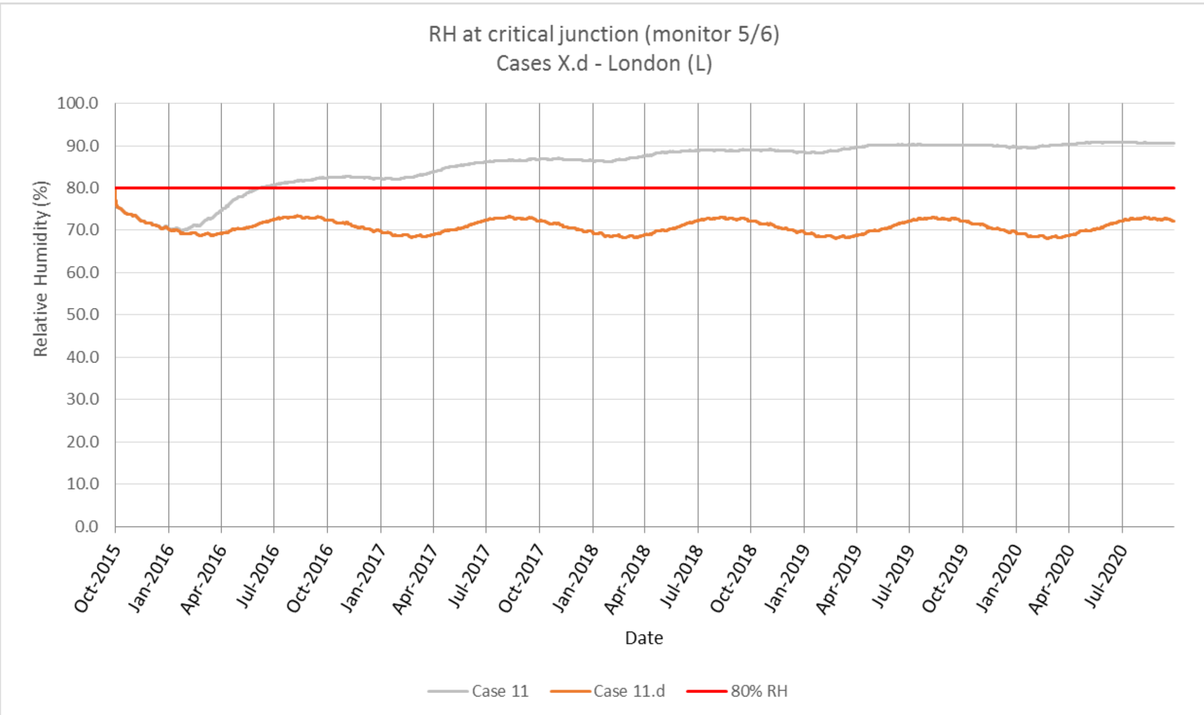


Figure 90: RH levels at critical junction for Cases 11 and 11.d (aerated clay brick)

15.8.6. Conclusions – Sensitivity Analysis Cases X.d

<u>Moisture risk assessment criteria</u>

Similarly to the sensitivity analysis with the ‘higher absorption’ brick, these graphs show that all cases modelled in this sensitivity analysis (using both ‘lower absorption’ bricks with the brick cream) performed better than their respective baseline cases where no brick cream is used.

All cases reach (or are close to reaching) equilibrium.

Aerated Clay Brick

For the aerated clay brick (sensitivity 2), the cases in the Zones 2, 3 and 4 display RH levels constantly staying around or above the 80% RH threshold. This means that these cases remain a ‘fail’. Like previous sensitivity cases, the impact of the measure tested (the use of brick cream) is not significant enough to change the status of these cases from ‘fail’ to ‘pass’. However, the case in Zone 1 displays equilibrium levels staying below the 80% threshold throughout the year. This means that this case can be described as a ‘pass’.

The table below summarises the performance of the sensitivity analysis cases:

Table 31: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	-	-	-	-
Part L	Case 2.d Fail	Case 5.d Risky	Case 8.d Fail	Case 11.d Pass
Other	-	-	-	-

Solid Brick Masonry

For the solid brick masonry (sensitivity 1), the cases in Zone 4 displays RH levels constantly staying around or above the 80% RH threshold. This means that this case remains a ‘fail’. However, the cases in Zones 1, 2 and 3 display equilibrium levels staying below the 80% threshold throughout the year. This means that these cases can be described as a ‘pass’.

This shows that the impact of the measure tested (the use of brick cream) becomes significant enough to change the status of these cases from ‘fail’ to ‘pass’ on most cases (except for the case in Zone 4) in these conditions (‘lower’ absorption brick with a low porosity, south-west façade, with this specific build-up in terms of insulation thickness and material, etc.).

The table below summarises the performance of the sensitivity analysis cases:

Table 32: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	-	-	-	-
Part L	Case 2.d Fail	Case 5.d Pass	Case 8.d Pass	Case 11.d Pass
Other	-	-	-	-

It is worth noting that both the internal wall insulation and the brick cream are installed simultaneously, on the 1 October (start date of the simulation), where these initial conditions are taken from the equilibrium results of an uninsulated wall WUFI model. This could mean that the sensitivity case modelled here are slightly worse than in reality, as the manufacturers' recommendations are to install brick cream on a 'dry' uninsulated wall.

Results

These results show that the upgraded build-up with brick cream (using both 'lower absorption' bricks) are made safer in terms of hygrothermal performance, compared to the build-up without brick cream.

This shows that the impact of the installation of brick cream leads to a significant enough improvement to change the status of some cases from 'fail' to 'pass':

- On the less exposed case (in Zone 1) for the aerated clay brick
- On most cases (except for the case in Zone 4) for the solid brick masonry

under these specific conditions (south-west façade, with this specific build-up in terms of insulation thickness and material, etc.).

Effects of exposure zones

Similarly to the application of brick cream on the 'higher absorption' brick, the effects of exposure zones is visible on the graphs, with the beneficial impact of the application of the brick cream on both 'lower absorption' bricks becoming increasingly visible the less exposed the zone in which the build-up is located.

15.9. Sensitivity Analysis – Combined measures

In order to assess if any combination of measures can be used to pass the risk assessment criteria for this build up for a larger number of cases, a wider range of further sensitivity analysis cases for the build-up have been modelled in varying combinations (with varying impacts) to identify the best possible performance. These include combinations of the following:

- The presence / absence of an air gap behind the internal insulation
- The presence of foil layers on either one side or both sides of the insulation layer
- Varying brick types (as investigated in previous sensitivity analysis)
- The addition of a “brick cream” layer to the build up
- The reduction of the thickness of the insulation material (and consequently the increase of its U-value)

It is worth noting that there are many other solutions available to insulate solid walls internally, with various mineral or organic materials applied in various forms which include or exclude the presence of vapour barriers. We have not modelled all solutions as this is beyond the scope of the existing project.

15.9.1. Sensitivity Analysis Cases

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the target U-value (as per baseline cases). We have applied the measures cumulatively as follows:

- Case X: As per baseline, for both ‘lower absorption’ bricks (Solid Brick Masonry for sensitivity 1, and Aerated Clay Brick for sensitivity 2) as per first sensitivity analysis)
- Case A: As per Case X, with the addition of brick cream
- Case B: As per Case A, with addition of adhesive mortar replacing the 15mm unventilated air layer
- Case C: As per Case B, with addition of foil layer (i.e. foil on both sides of the insulation, rather than just the inside)

These cases are modelled in each climate zone.

15.9.2. Graphs at Critical Junction

All graphs 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.

The graphs are displayed for each of the cumulative cases across the four exposure zones, with the sensitivity analysis cases shown as a different shades of coloured lines (blue for Swansea, purple for Bristol, green for Manchester and orange for London), while the Case X baseline cases are shown as a grey line.

- <u>Sensitivity 1: Solid Brick Masonry</u>

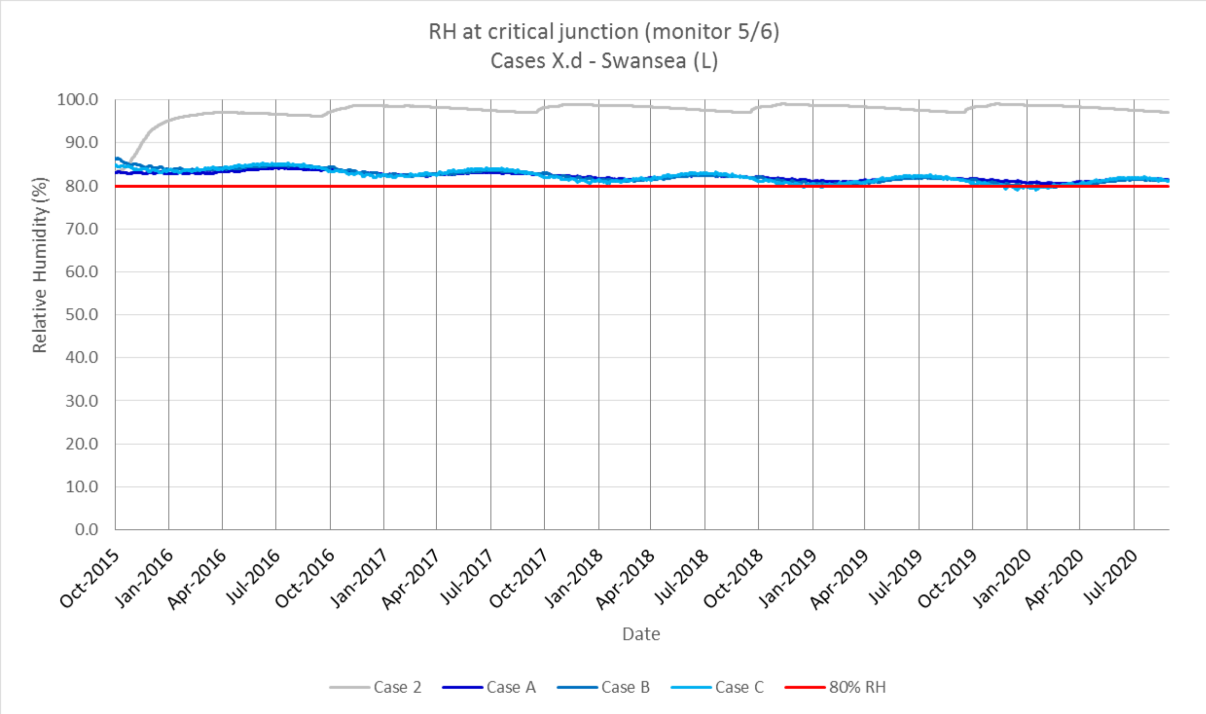


Figure 91: RH levels at critical junction for Cases 2, A, B and C for Zone 4 (masonry brick)

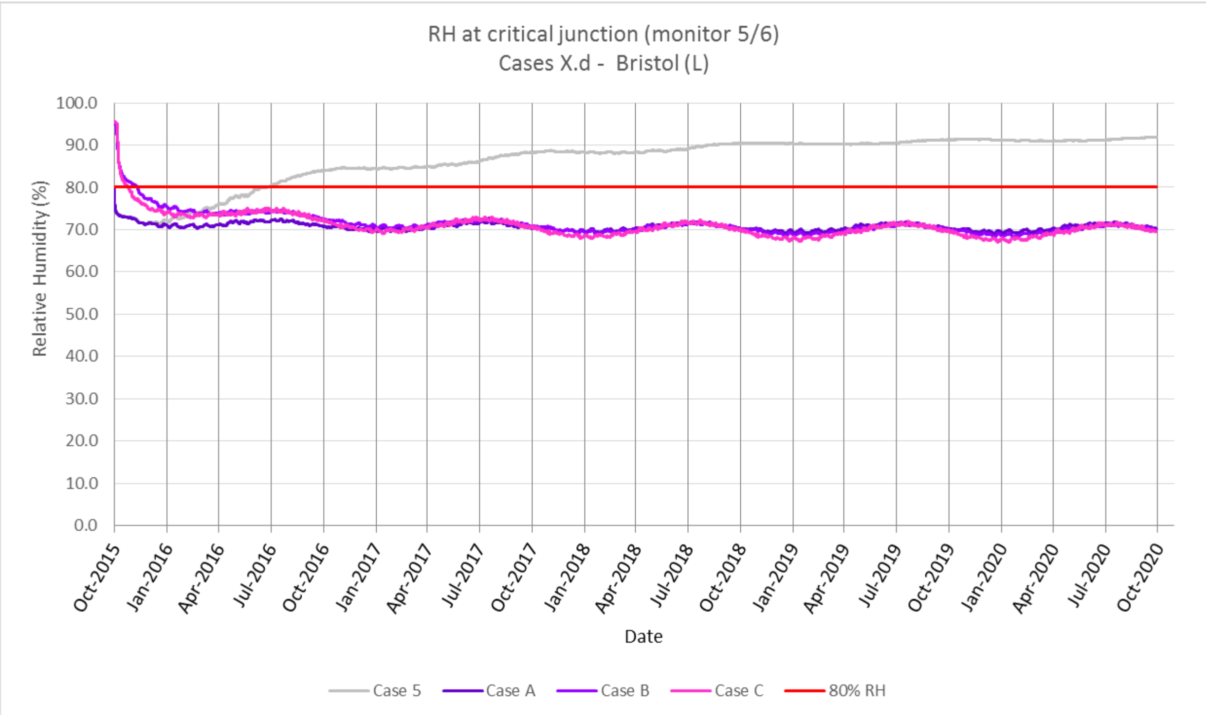


Figure 92: RH levels at critical junction for Cases 5, A, B and C for Zone 3 (masonry brick)

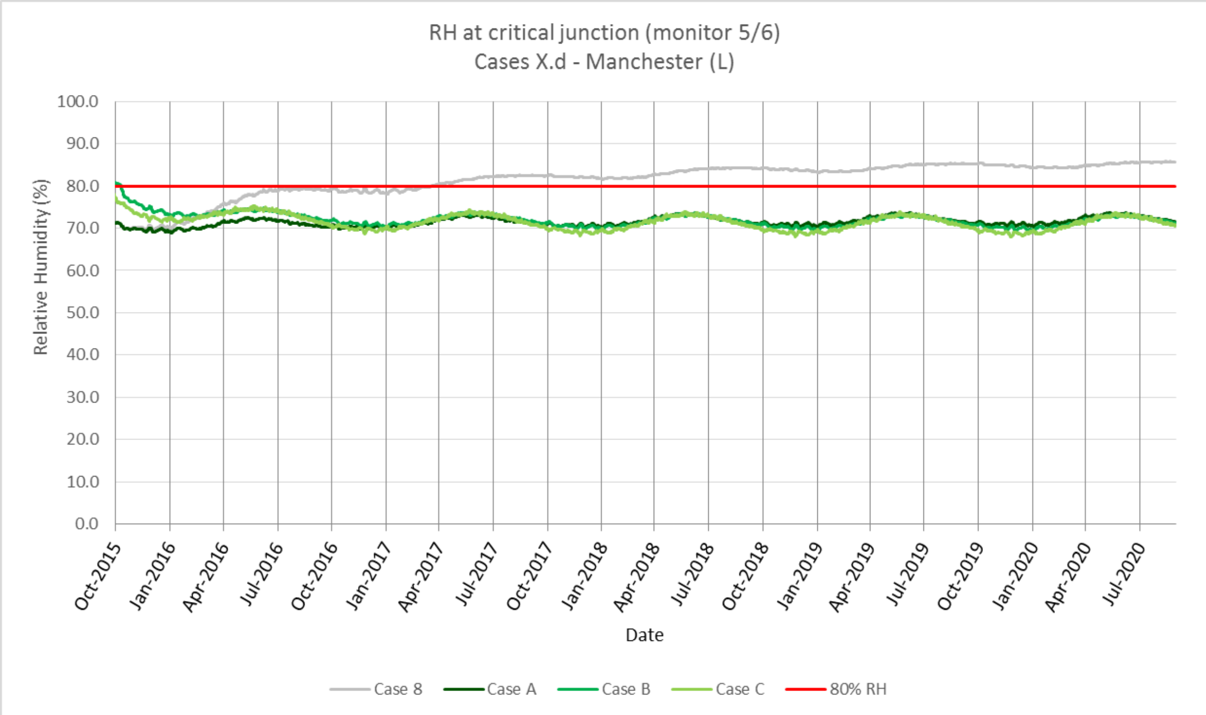


Figure 93: RH levels at critical junction for Cases 8, A, B and C for Zone 2 (masonry brick)

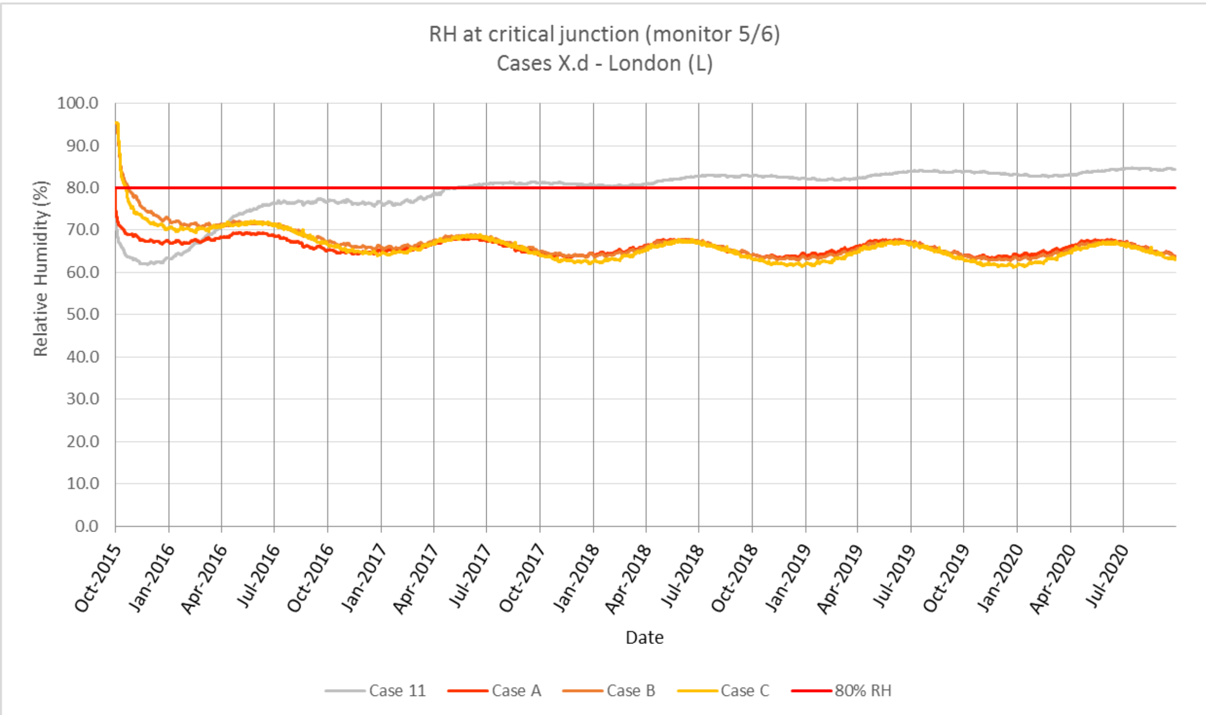


Figure 94: RH levels at critical junction for Cases 11, A, B and C for Zone 1 (masonry brick)

- <u>Sensitivity 2: Aerated Clay Brick (650 kg/m3)</u>

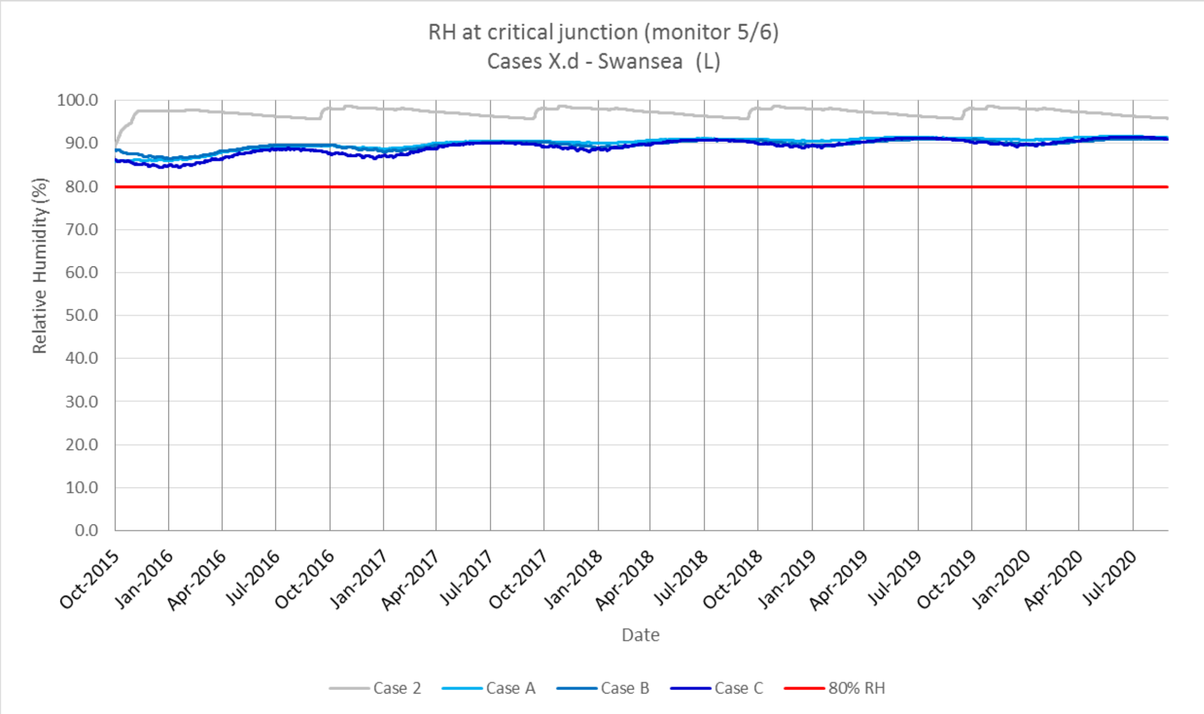


Figure 95: RH levels at critical junction for Cases 2, A, B and C for Zone 4 (aerated clay brick)

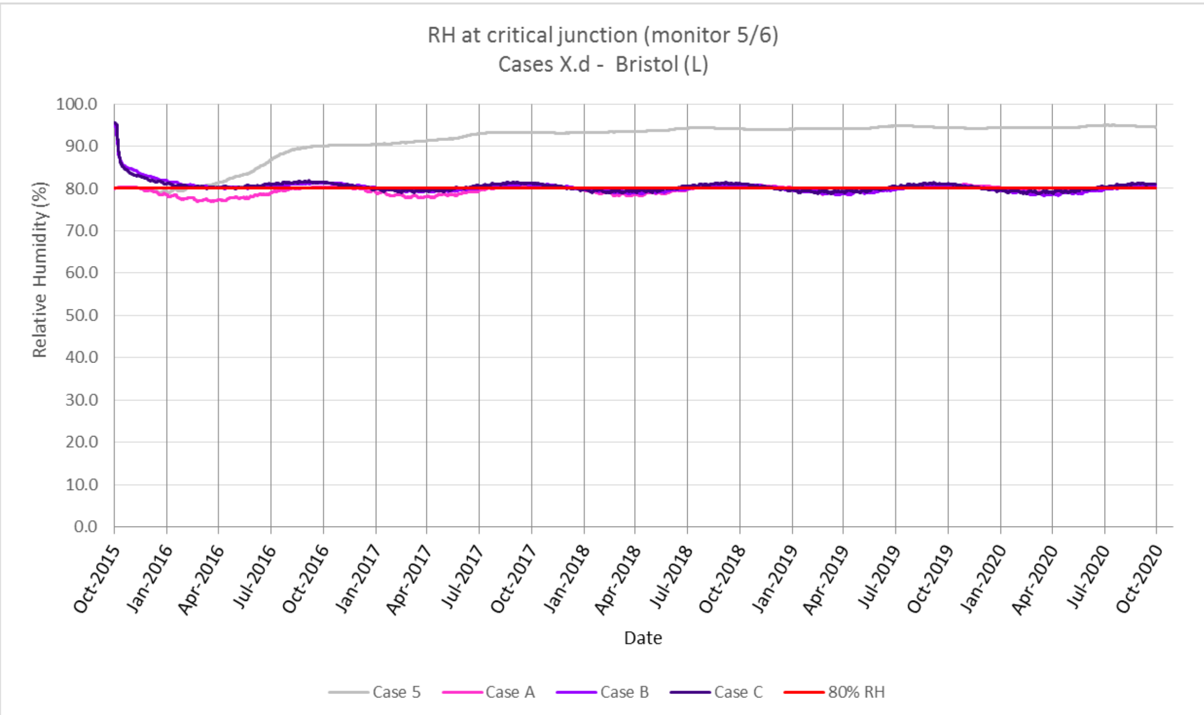


Figure 96: RH levels at critical junction for Cases 5, A, B and C for Zone 3 (aerated clay brick)

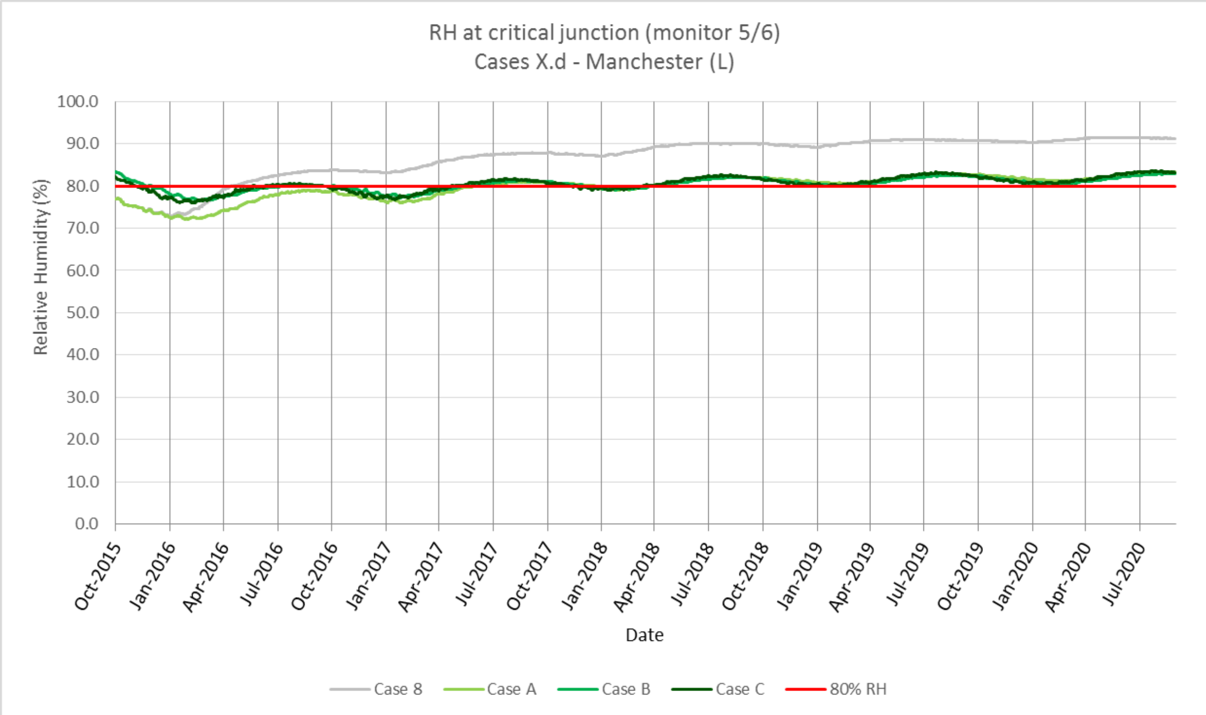


Figure 97: RH levels at critical junction for Cases 8, A, B and C for Zone 2 (aerated clay brick)

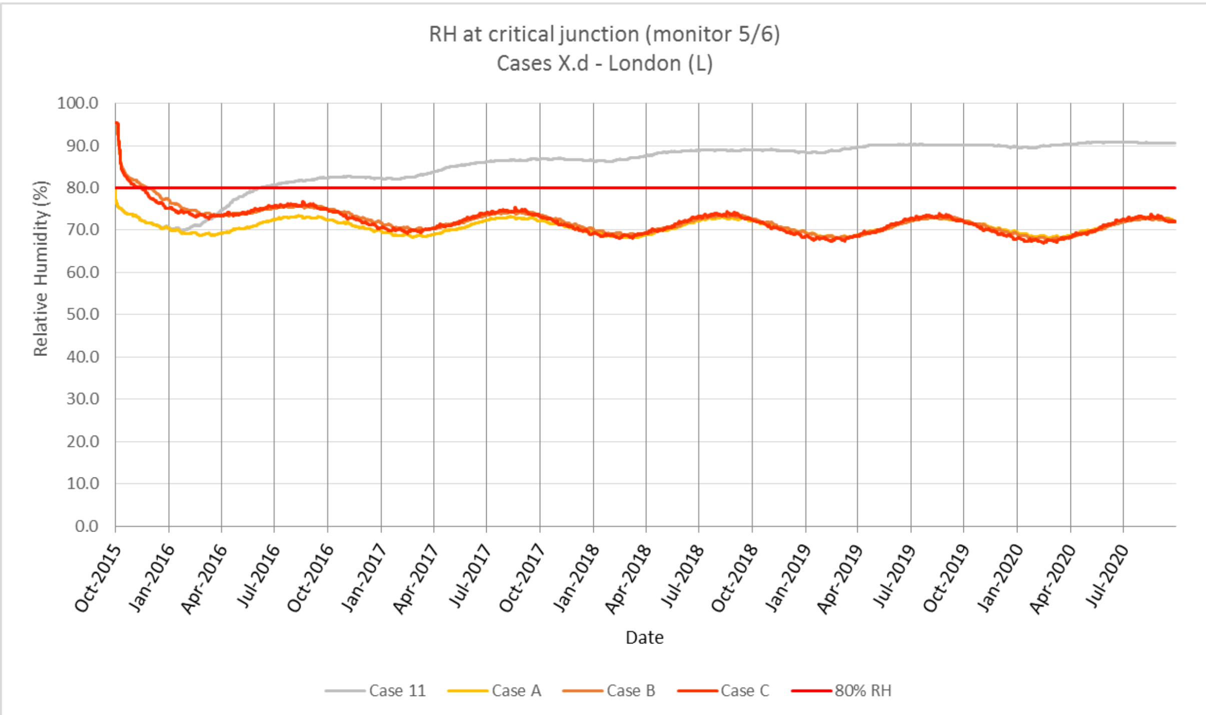


Figure 98: RH levels at critical junction for Cases 11, A, B and C for Zone 1 (aerated clay brick)

15.9.3. Conclusions – Sensitivity Analysis Cases

Moisture risk assessment criteria
The graphs show that, independently to which of the two 'lower absorption' bricks is used, the impact of these additional measures (as listed below) have a negligible impact:

- The presence / absence of an air gap behind the internal insulation
- The presence of foil layers on either one side or both sides of the insulation layer

The only additional measure that makes a significant enough difference to improve the status of the modelled cases is the addition of the brick cream layer (in addition to the variation in brick types which was investigated as the first sensitivity analysis)

Solid Brick Masonry

Out of the two 'lower absorption' bricks tested in these sensitivity analysis, the Solid Brick Masonry always display better results (with RH levels at the critical junction constantly kept lower for this brick).

As highlighted in the previous section, all scenarios show substantial improvement for this brick over the baseline cases in each climate zone and are considered 'safe', with the only exception of the Zone 4 case (Swansea), which remains above 80% RH and is considered a 'fail' in accordance with the moisture risk assessment criteria.

Additional Modelling –Thinner insulation

In order to see if this build-up can be made 'safe' in Zone 4 (Swansea – being the only zone in which this case is considered a 'fail'), additional modelling was undertaken making the insulation thinner.

The build up with the Solid Brick Masonry brick type and brick cream was modelled with thinner insulation (25mm – the thinnest practically possible) for the Swansea (Zone 4) climate, against its baseline case (with an 80mm insulation layer).

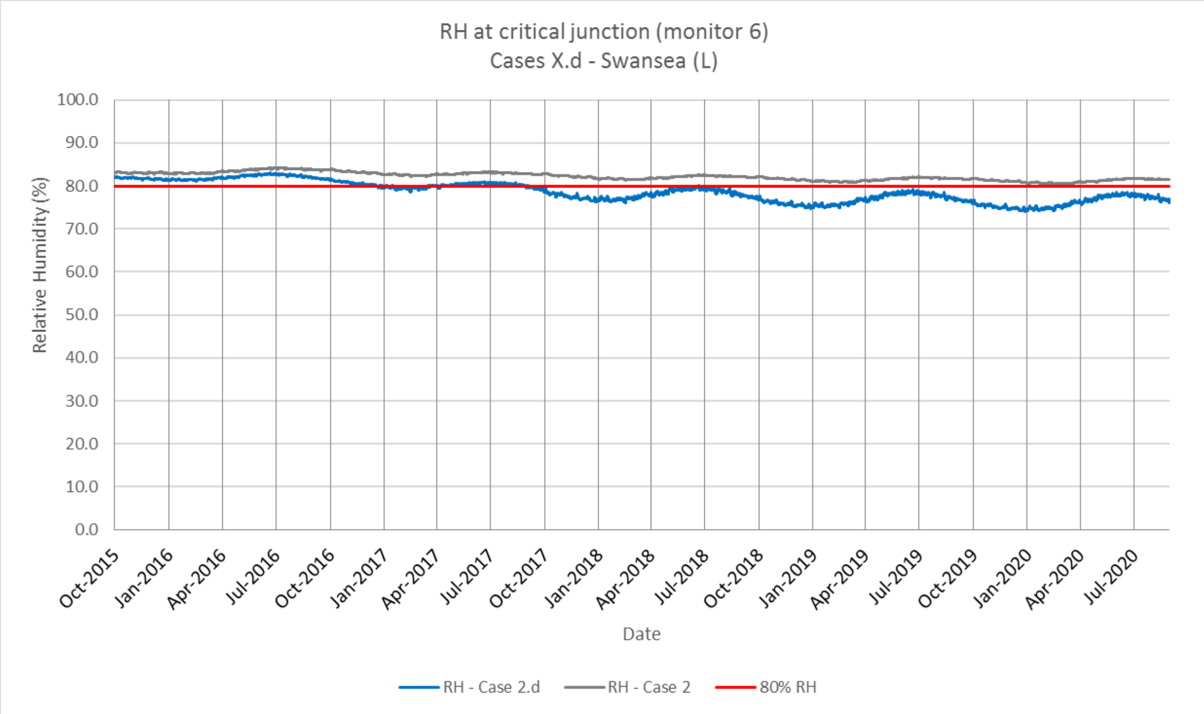


Figure 99: RH levels at monitored junction for Cases 2 and 2.d

The graph shows that the moisture levels in the wall are improved and stabilise just below 80% RH, but moisture levels remain high initially for a period lasting over a year, meaning the build-up fails the moisture risk assessment criteria.

Therefore, despite this measure (reduction in insulation layer) having a more important impact than testing on a ‘higher absorption’ brick with brick cream (see section 15.6), this measure is not sufficient enough to change the status of the Zone 4 case, still considered a ‘fail’.

Results

The table below summarises the performance of the modelled cases, using both ‘lower absorption’ bricks (Aerated Clay Brick and Solid Brick Masonry) with the application of brick cream:

Table 33: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Cases A,B &C	Case 2.d Fail	Case 5.d Risky (dependant on brick type)	Case 8.d Risky (dependant on brick type)	Case 11.d Pass
Other	-	-	-	-

The results show that the change in the external layer characteristics of the brick (i.e. addition of brick cream) has the most significant impact on the hygrothermal performance of the build-up and this dominates other minor changes (such as the presence / absence of foil layers and unventilated air layers).

However, the results show that the impact of the brick cream, in terms of whether the build-up passes or fails the moisture risk assessment criteria (RH levels less than 80% at the critical junction), depends heavily on the original substrate brick type and its corresponding moisture-related properties. As stated earlier, these properties are not well characterised currently for traditional UK bricks.

In addition, the exposure zone always play a significant role in all cases, as the build-up even with thinner insulation ‘fails’ in Swansea (zone 4) climate due to high initial RH levels (over the first couple of years) at the critical junction.

15.10. Conclusions

- This build-up is very risky in ‘theoretical’ conditions
- BS EN 15026 is the only adequate method to assess this construction (though still not standardised)
- Further analysis on this construction can be seen the *Using numerical simulation to assess moisture risk in retrofit constructions. Part 2* report

16. Typology R9: Solid masonry Retrofit Measure: External Wall Insulation (EWI)

The R9 typology is a solid, uninsulated brick wall prior to retrofit. The retrofit measure is to insulate the wall externally with closed-cell insulation and a non-porous finish (silicone render).

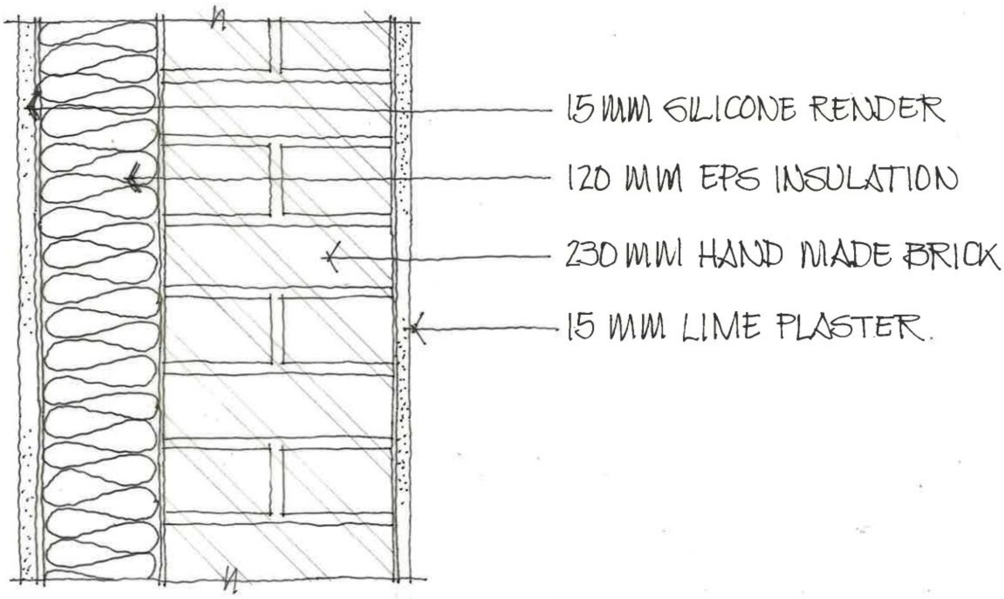


Figure 100: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

16.1. Assessment Method

The build-up contains porous materials having the capacity to store moisture, however, the porous material (solid masonry wall)'s external surface is not directly exposed to the elements (rain, wind and radiations) due to additional layers installed externally to the masonry wall. Therefore, the BS EN ISO 13788 (2012) assessment method is valid for this typology, for the equilibrium state. Indeed, the fact that the insulation layer is added as a retrofit measure onto a potentially damp solid wall means that in practice, the initial conditions differ from the default input data used in the BS EN ISO 13788 (2012) calculation.

Despite this difference in initial conditions, both BS EN ISO 13788 (2012) and WUFI modelling following BS EN 15026 (2007) should display similar results for the equilibrium state. The results by the Glaser method show that this build-up is considered a 'safe' build-up, with no risk of interstitial condensation throughout the year. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

16.2. Build-up

16.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 230mm solid brick (hand-formed)
- 15mm lime plaster

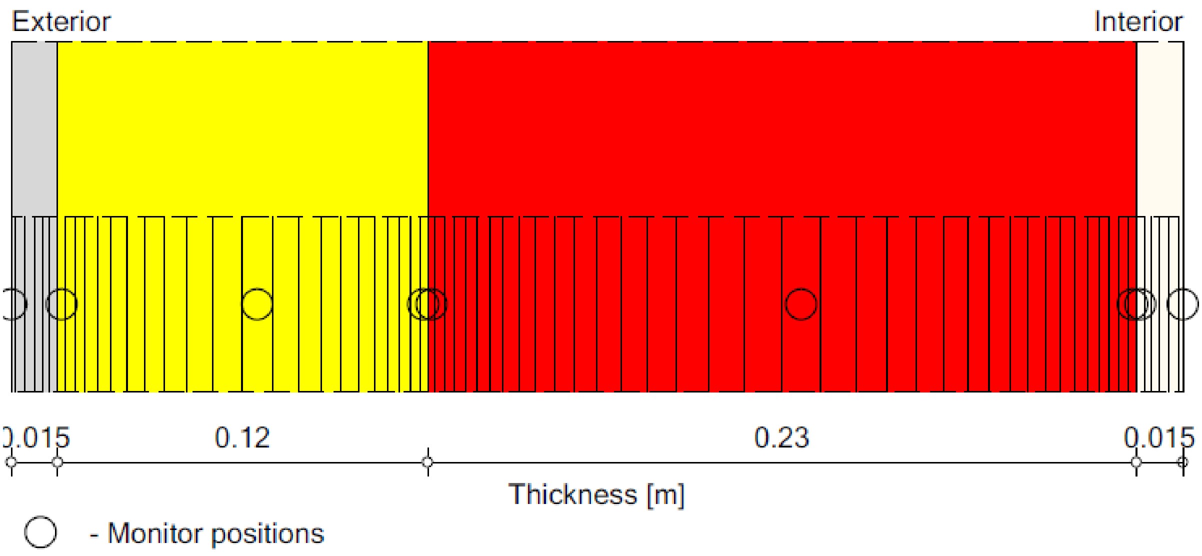
16.2.2. Initial Conditions

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.

16.2.3. WUFI Build-up (post-retrofit)

Build-Up:

- 15mm silicone render
- 120mm EPS insulation (λ = 0.040 W/m.K)
- 230mm solid brick (hand-formed)
- 15mm lime plaster



Materials:

- Silicon Resin Finishing Coat 0.015 m
- EPS (heat cond.: 0.04 W/mK - density: 15 kg/m³) 0.12 m
- Solid Brick, hand-formed 0.23 m
- Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5) 0.015 m

16.3. Baseline Results

16.3.1. Baseline Cases

The 8 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 34: 4 baseline cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

16.3.2. Monitored Junction

Moisture problems tend to be exacerbated at interfaces, as they are locations at which moisture can accumulate or get trapped. In this case, the interface between the retrofitted insulation and the existing solid masonry wall is located on the warm side of the insulation. Therefore, this junction should not be at risk as its temperature should be kept above the dew point. This interface is the monitored junction for this typology, as this is the interface at which moisture could get trapped.

16.3.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction, i.e. the interface between the retrofitted insulation layer and the existing solid masonry wall, located on the warm side of the insulation.

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).

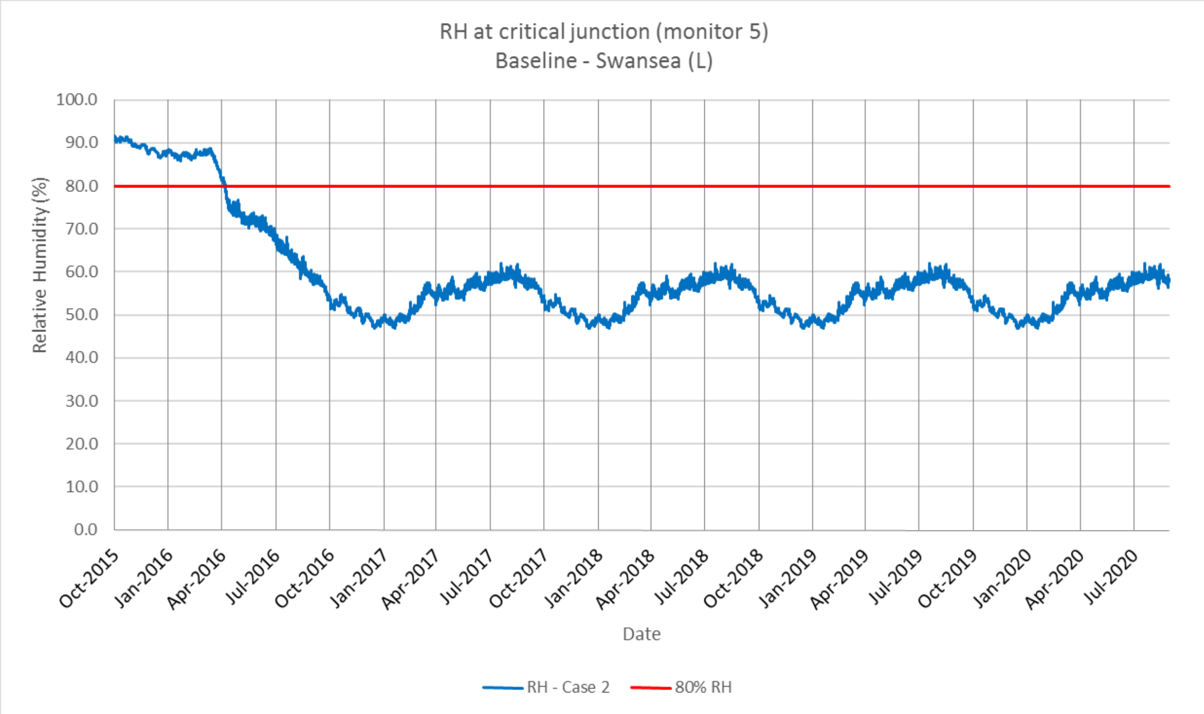


Figure 101: RH levels at monitored junction for Case 2

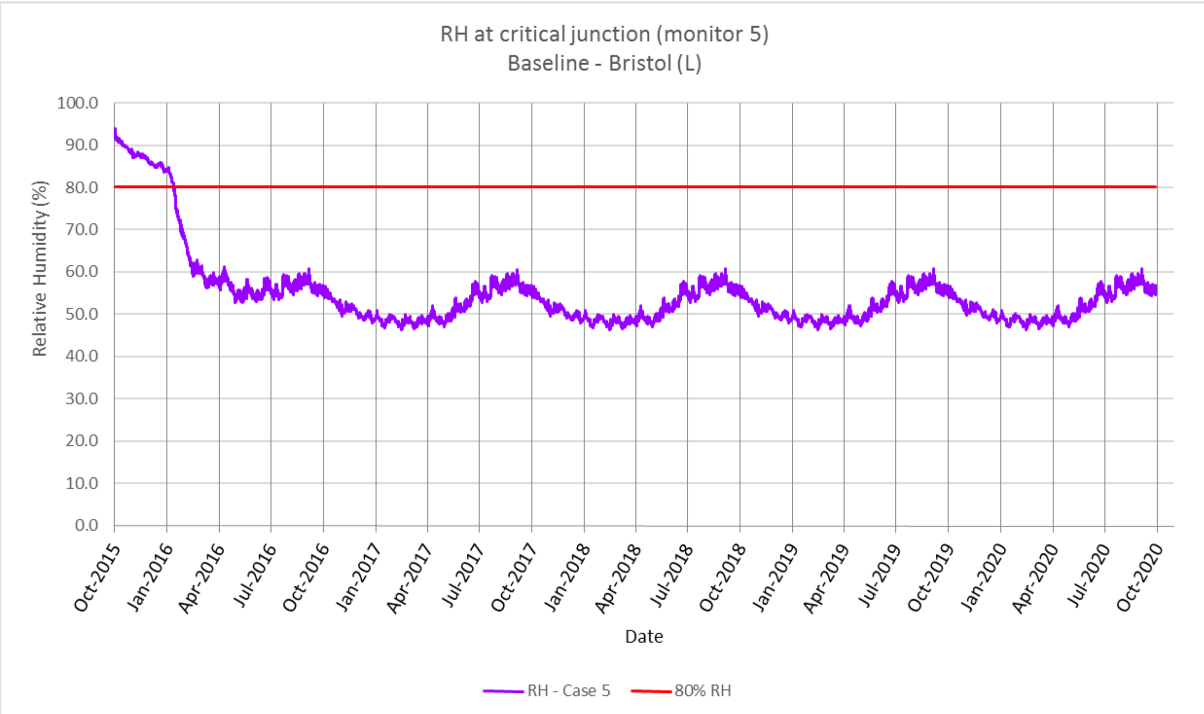


Figure 102: RH levels at monitored junction for Case 5

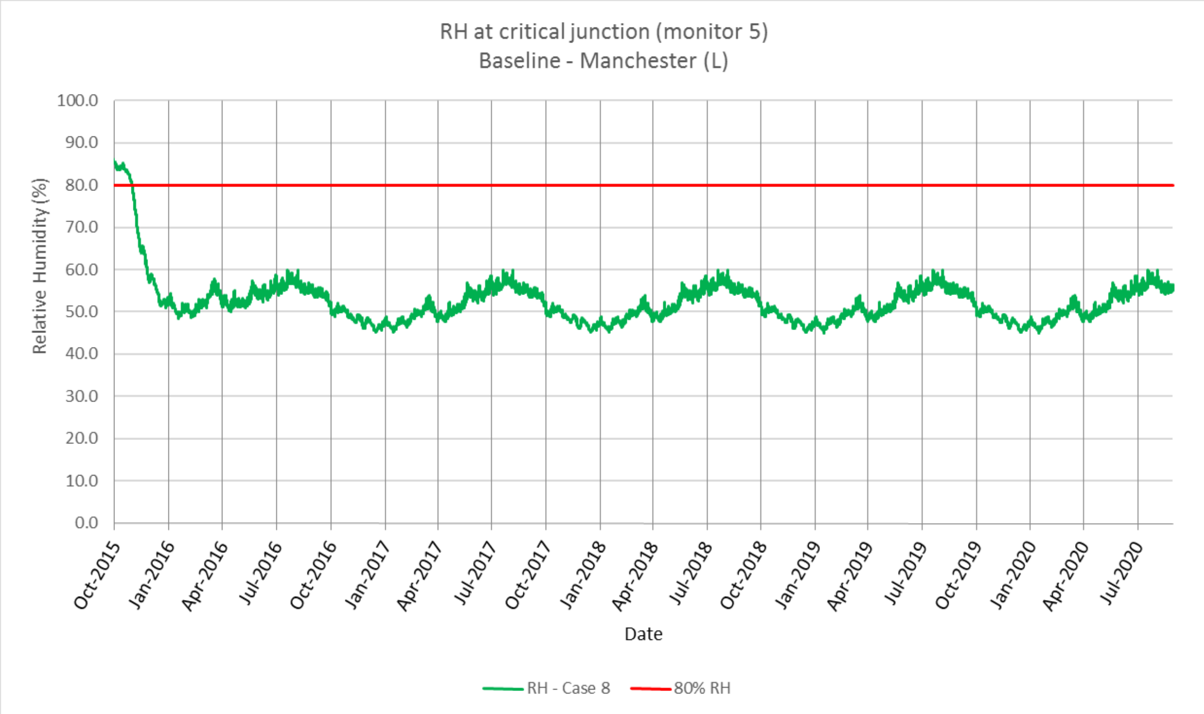


Figure 103: RH levels at monitored junction for Case 8

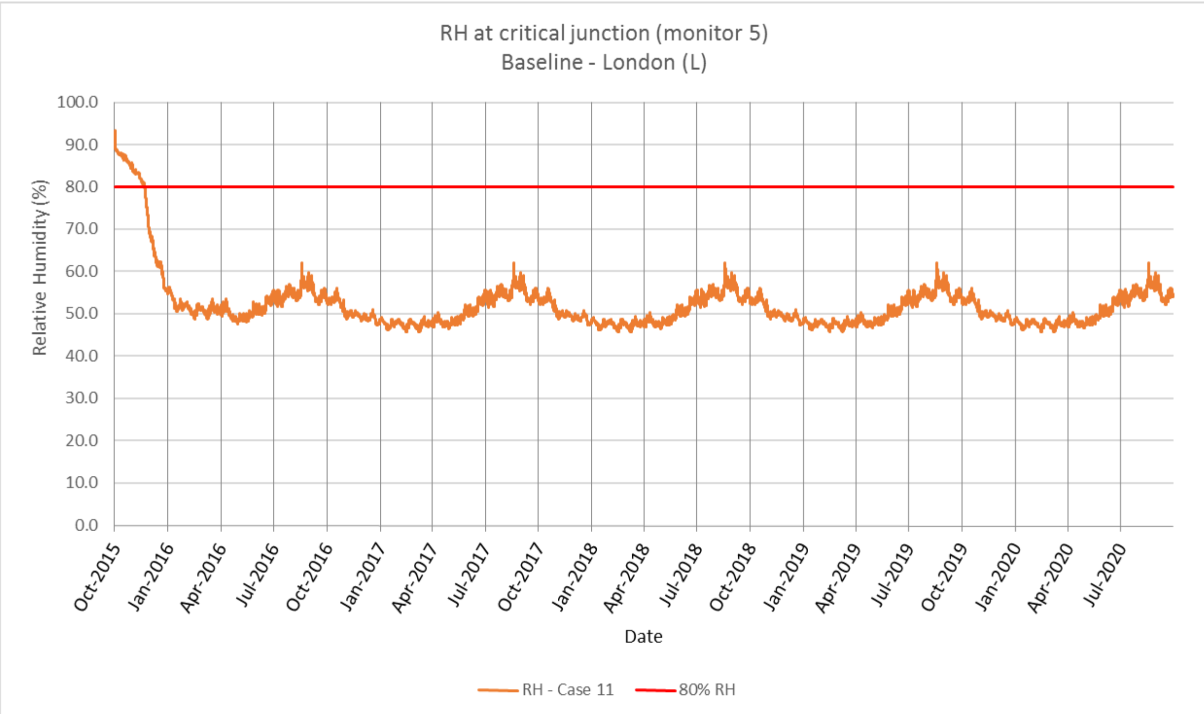


Figure 104: RH levels at monitored junction for Case 11

16.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>

As predicted, all scenarios are considered as 'pass' as they are all drying out towards equilibrium. All cases have RH levels well below the 80% RH threshold, despite high initial RH levels caused by the fact that the existing solid wall was exposed to wind-driven rain and contained high levels of moisture prior to the installation of the retrofit measure.

Cases in exposure zones 1, 2 and 3 are considered to be clear 'pass'. However, the case in Zone 4 – Swansea is on the limit of being considered 'risky', as it takes just about six months for the initial RH levels to go below the 80% RH threshold (with six months being the limit set in the third moisture risk assessment criteria in section 2.3).

These results are summarised in the table below.

Results

Table 35: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
Other	-	-	-	-

These findings are in line with current practice in the industry, as this is one of the typologies considered highly resistant to moisture (when installed adequately).

Effects of exposure zones

The effect of wind-driven rain exposure zones is almost undistinguishable on the graphs, as RH levels at the monitored junction look similar for all cases and are well within the 'safe' RH levels. The only difference visible due to different exposure zones is the length it takes for the initial RH levels to go below the 80% RH threshold. The more exposed the zone is, the longer the period of high initial RH levels (with the conditions experienced in Zone 4 – Swansea reaching the limit between 'pass' and 'risky').

This confirms that this typology is considered good regarding its resistance to moisture. The only proviso is the impact of poor starting conditions (i.e. damp existing solid wall) with build-ups located in highly exposed zones (Zone 3 - Bristol or Zone 4 – Swansea), which delays the time needed for the wall to reach equilibrium and therefore decreases its hygrothermal performance.

16.3.5. Conclusions – Baseline

In accordance with current best practice in the industry, this typology is found to be resistant to moisture, regardless of the wind-driven rain exposure zone the build-up is located in, as the RH levels at the monitored junction are well within the ‘safe’ RH levels after they stabilise. This is due to the interface between the insulation and the solid brick layer being kept above the dew point, as a result of the insulation layer.

However, initial conditions, more particularly moisture content in the existing solid masonry wall and the exposure zone in which the build-up is located, can have a significant effect on the hygrothermal performance of the build-up (as shown in the Swansea case).

The equilibrium results from WUFI modelling are also in accordance with calculations done following the BS EN ISO 13788 (2012) method, which demonstrates no interstitial condensation risk in this build-up

16.4. Sensitivity Analysis – Change in Material [Cases X.d]: Change external finish from render to brick slips

16.4.1. External Layer Physical Characteristics

This typology includes a relatively non-porous material (the outer render layer) being exposed to wind-driven rain and solar gains. The transient modelling of other typologies indicates that the physical characteristics of the external layer play a significant role on the hygrothermal performance of a build-up. Therefore, the first sensitivity analysis is carried out with a change in the external layer from a render layer to a more absorbent layer of brick slips, adhered to the insulation using adhesive.

This brick used in this sensitivity analysis is called Aerated Clay Brick (650 kg/m^3) and can be described as a low absorption brick (compared to the rest of the bricks present in the WUFI database). This choice of brick is likely to represent the characteristics of brick slips currently used in the industry. It has a relatively low density (linked to a higher porosity) compared to the ‘solid brick (hand-formed)’ used for the existing solid masonry wall, and has a mid-range A-value of 0.097 $kg/m^2\sqrt{s}$.

16.4.2. Sensitivity Analysis Cases

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the target U-value (as per baseline cases):

Table 36: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
Other				

16.4.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction (which is the same as in the baseline cases). The graphs are displayed for the sensitivity cases across the four exposure zones, with the sensitivity analysis cases shown as a coloured line (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1), while their respective baseline cases are shown as a grey line.

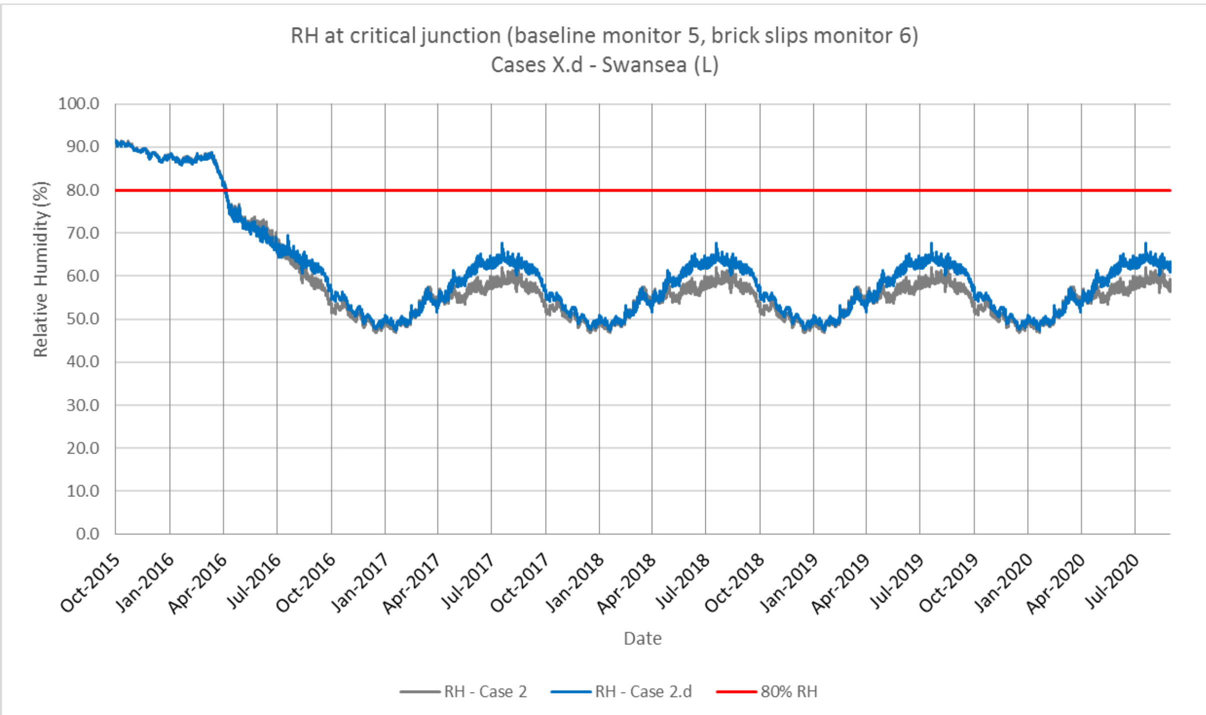


Figure 105: RH levels at monitored junction for Cases 2 and 2.d

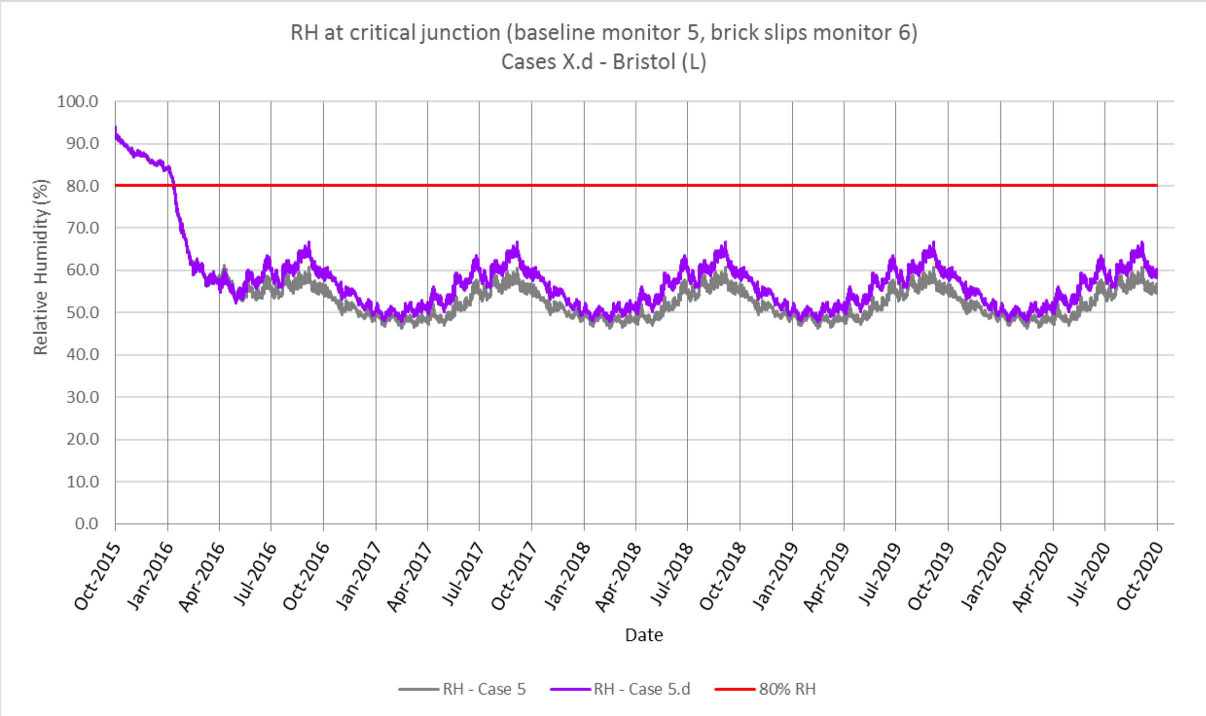


Figure 106: RH levels at monitored junction for Cases 5 and 5.d

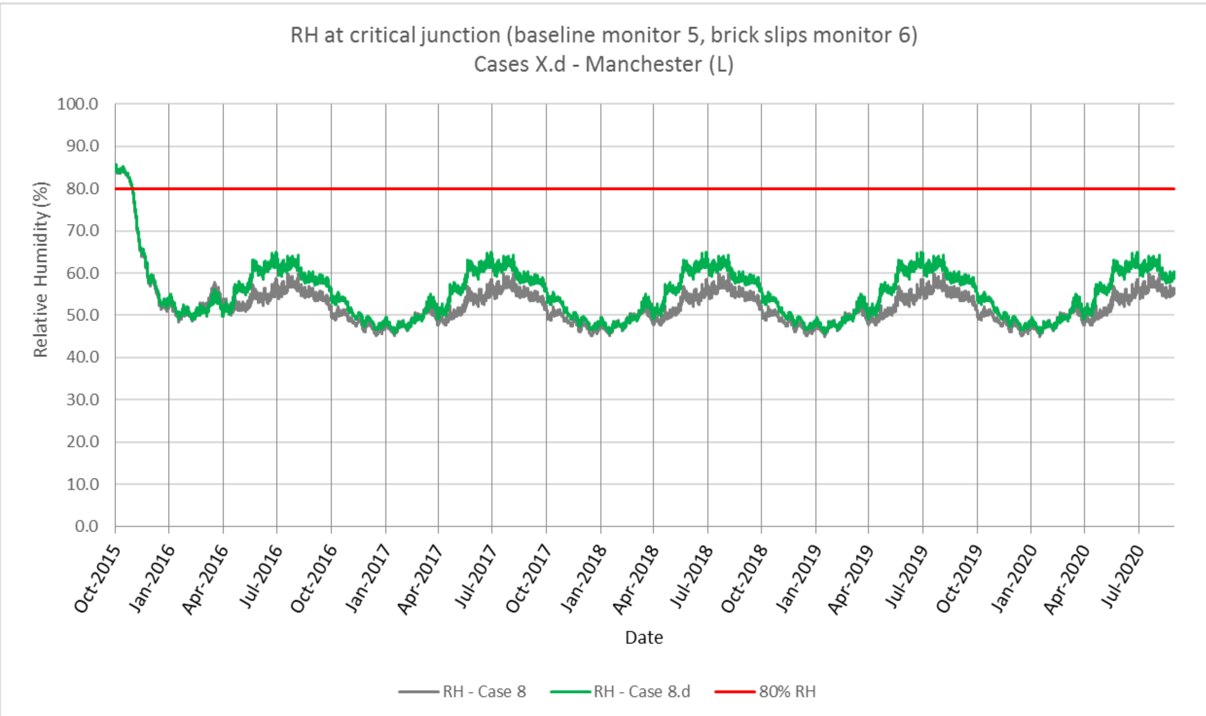


Figure 107: RH levels at monitored junction for Cases 8 and 8.d

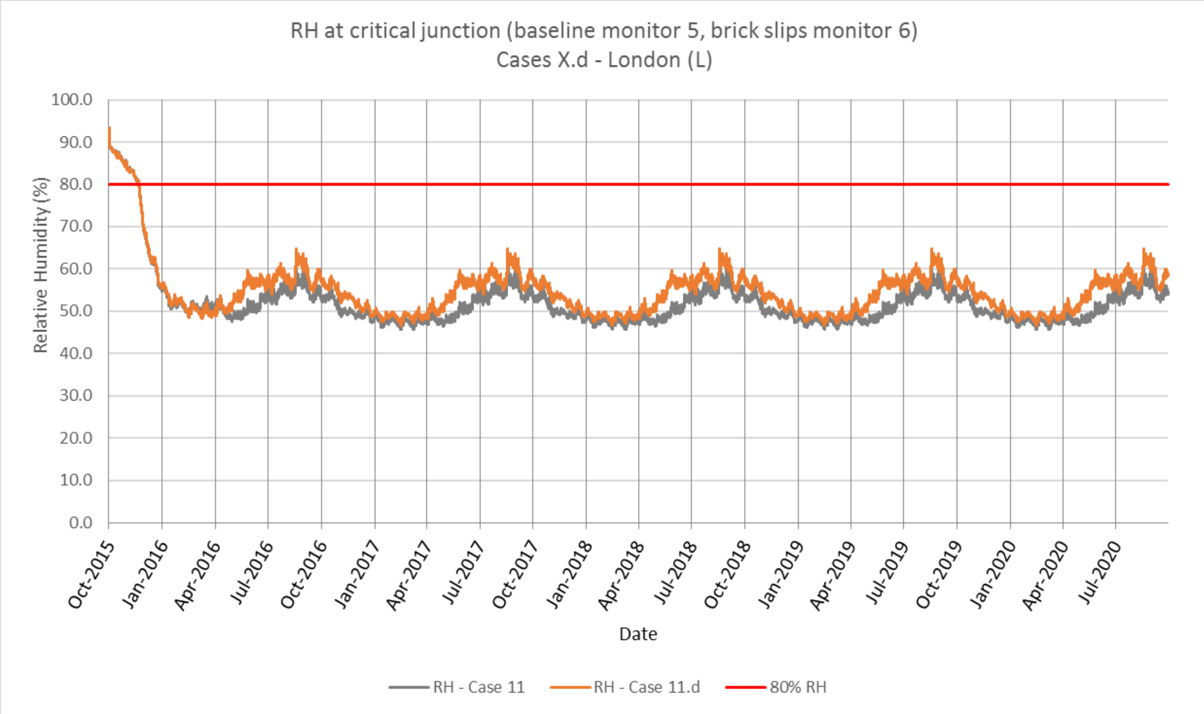


Figure 108: RH levels at monitored junction for Cases 11 and 11.d

16.4.4. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria
The graphs show that all cases which are modelled in this sensitivity analysis perform slightly worse than their respective baseline cases, as the RH profiles in the sensitivity analysis are consistently equal or higher than their respective baseline.

However, this reduction in hygrothermal performance is not significant, as RH levels at equilibrium are consistently maintained below the 80% RH threshold. This means that all cases retain the same status as those in the baseline assessment and considered ‘safe’ in accordance with the moisture risk assessment criteria.

Results
The table below summarises the performance of the modelled cases:

Table 37: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2.d Pass	Case 5.d Pass	Case 8.d Pass	Case 11.d Pass
Other	-	-	-	-

These graphs show that, on average, the change external layer characteristics has a limited impact on the hygrothermal performance of the build-up, despite the change from a render finish (non-porous) to a brick slip finish (using actual bricks, therefore a much more porous material). These results show that this build-up remains a robust build-up regarding its resistance to moisture, with reasonable RH levels kept at the monitored junction.

16.5. Conclusions

In accordance with current best practice in the industry, this typology is found to be resistant to moisture, regardless of the wind-driven rain exposure zone the build-up is located in, as the RH levels at the monitored junction are well within the 'safe' RH levels after they stabilise. This is due to the interface between the insulation and the solid brick layer being kept above the dew point, as a result of the insulation layer.

The results are also in accordance with calculations done following the BS EN ISO 13788 (2012) method, which demonstrates no interstitial condensation risk in this build-up.

The build-up is considered 'safe' in all exposure zones, but care needs to be taken to ensure as much as possible 'dry' initial conditions of the existing solid brick wall (as well as the insulation layer) to reduce the initial period of high RH levels due to the initial moisture content present in the solid brick wall prior to retrofit. These performance results are not significantly altered when the non-porous finish (render) is changed for a porous finish (brick slips).

Extra case is also required, related to the ABIS conditions and workmanship quality issues. These include the external finish quality - no cracks and gaps where water can get behind, as well as limiting thermal bridging at junctions and areas where insulation is interrupted (meter boxes, etc.).

17. Typology R11.1: Cavity masonry (uninsulated) Retrofit Measure: Internal 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.

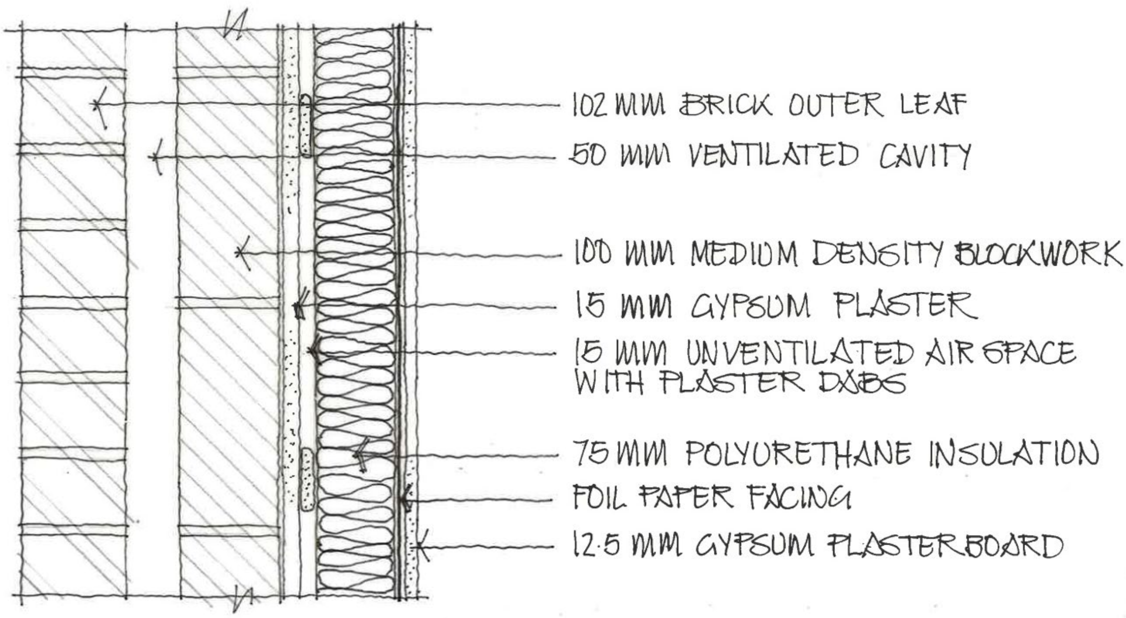


Figure 109: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

17.1. Assessment Method

As BS 5250 (2011) states in the cavity wall section (G.3.2.1), *'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). Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method.

The results by the Glaser method show that this build-up is generally considered to be a ‘safe’ build-up, with no risk of interstitial condensation throughout the year. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

17.2. Build-up

17.2.1. 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

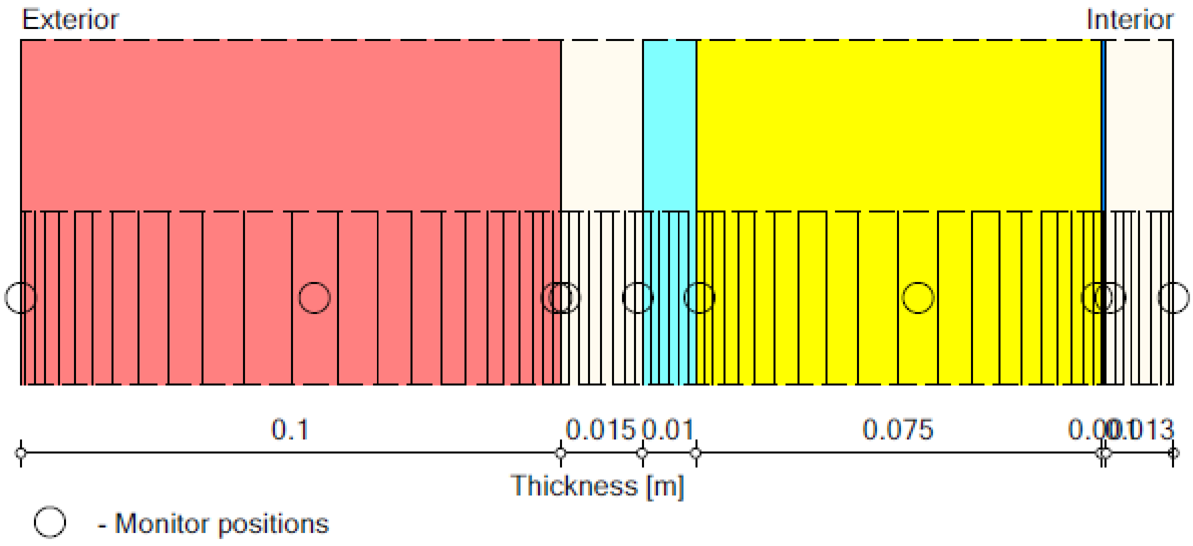
17.2.2. Initial Conditions

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.

17.2.3. WUFI Build-up (post-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
- 15mm unventilated layer with plaster dabs
- 75mm PU foam insulation
- 1mm foil paper facing (sd = 14m)
- 12.5mm gypsum plasterboard



Materials:

	- *Blockwork - medium density	0.1 m
	- Interior Plaster (Gypsum Plaster)	0.015 m
	- *Air Layer 15 mm; without additional moisture capacity (unlocked)	0.01 m
	- *PU (heat cond.: 0,025 W/mK)	0.075 m
	- *Foil paper facing (sd = 14m) (unlocked)	0.001 m
	- Gypsum Board	0.013 m

<u>WUFI Input Parameters</u>

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 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

17.3. Baseline Results

17.3.1. Baseline Cases

The 8 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 38: 4 baseline cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1	Case 4	Case 7	Case10
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

17.3.2. 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.3.2.4 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’*.

17.3.3. 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).

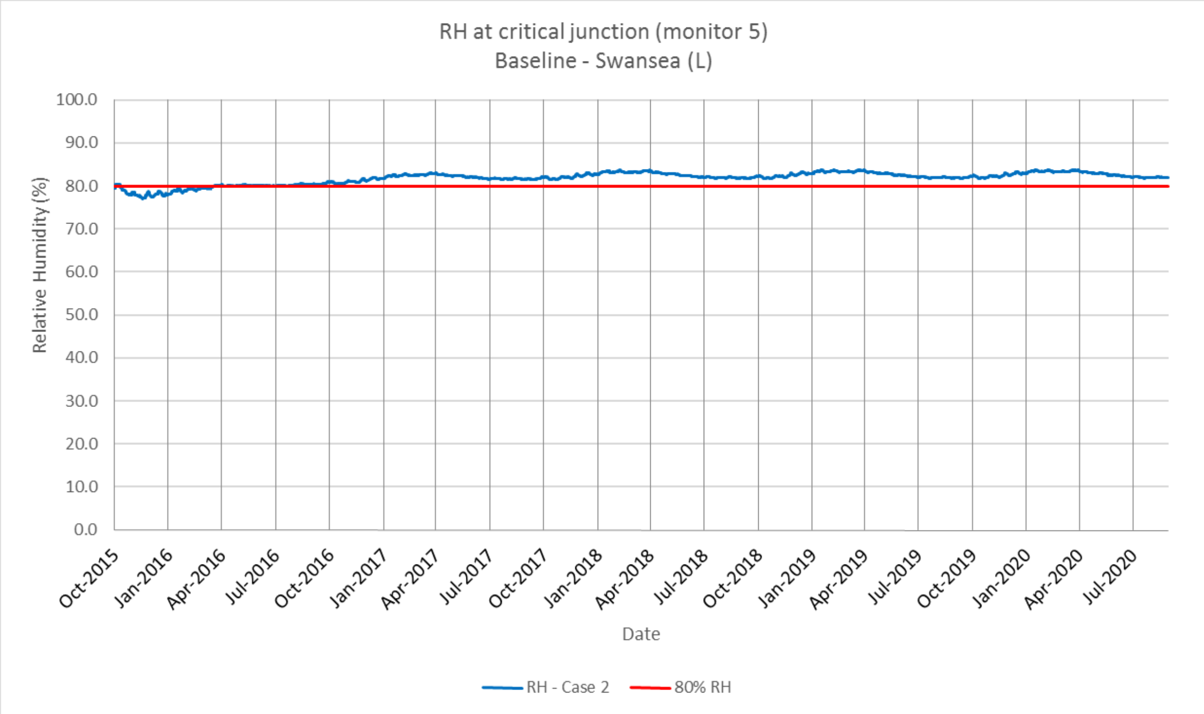


Figure 110: RH levels at critical junction for Case 2

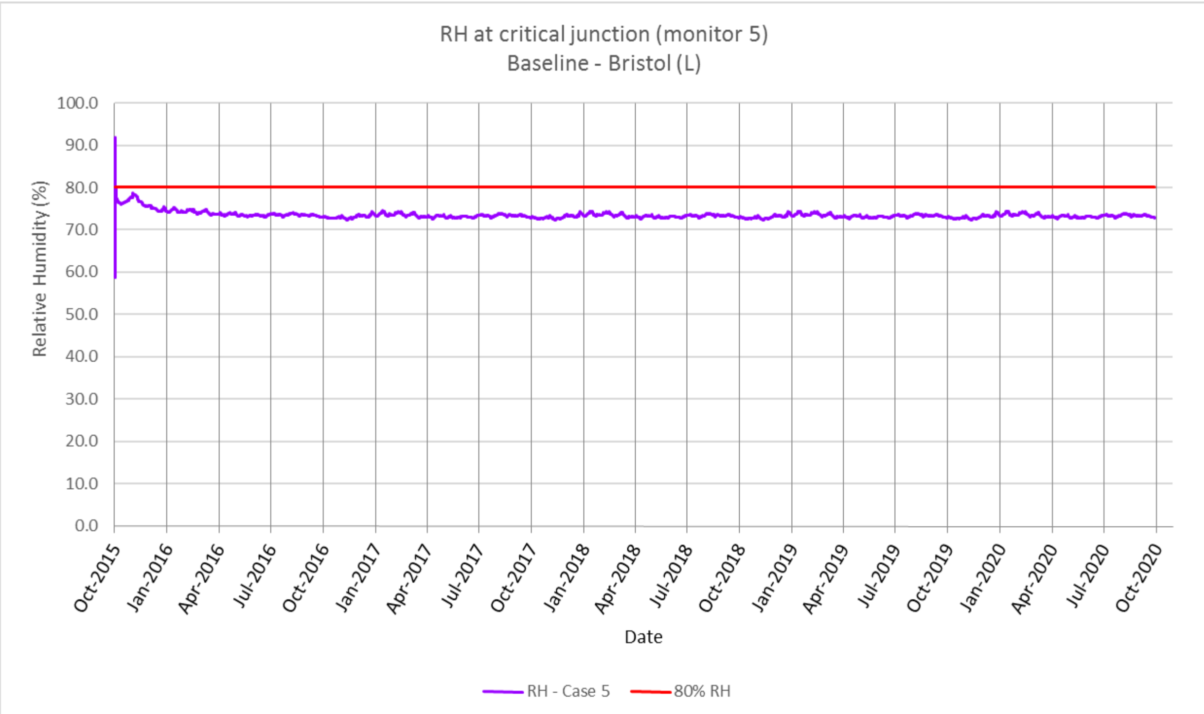


Figure 111: RH levels at critical junction for Case 5

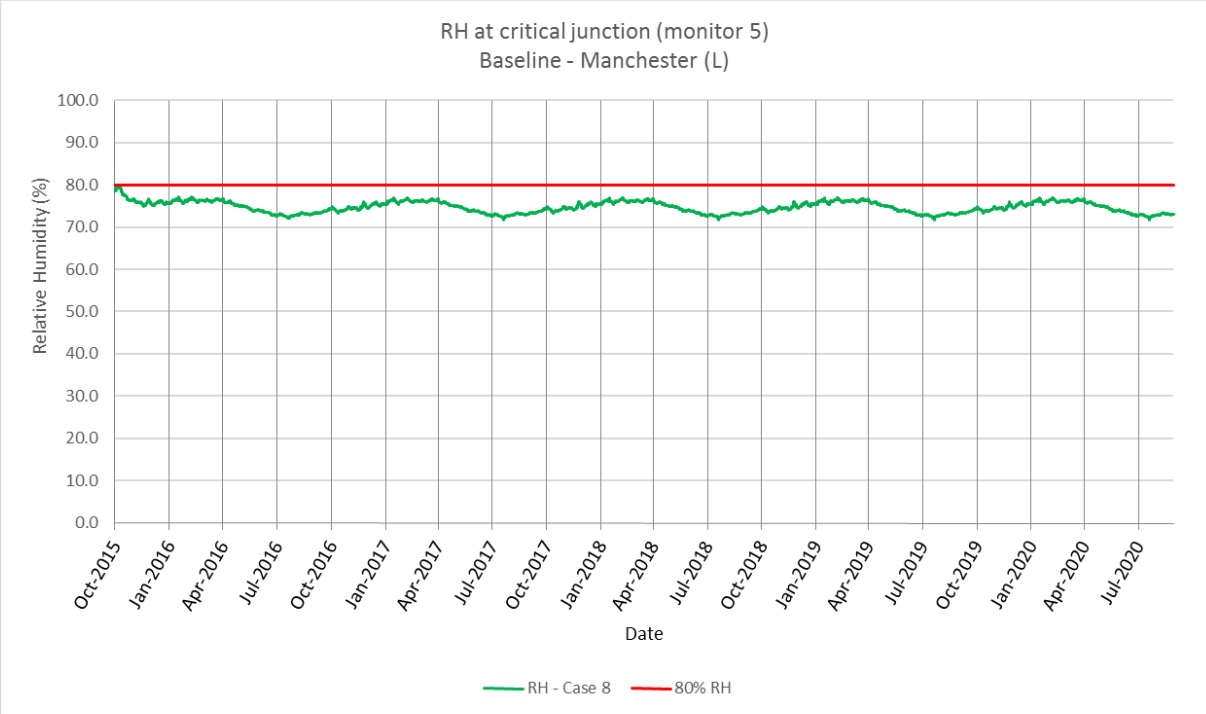


Figure 112: RH levels at critical junction for Case 8

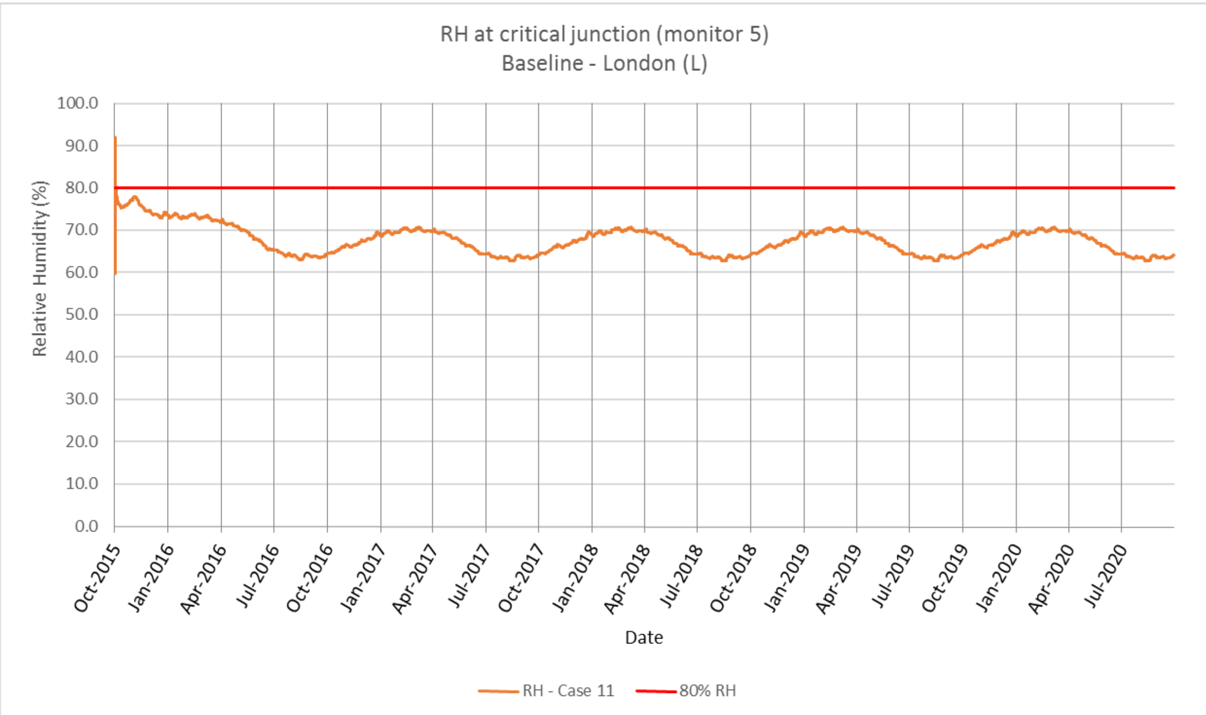


Figure 113: RH levels at critical junction for Case 11

17.3.4. Results Analysis

Moisture risk assessment criteria

All scenarios achieve equilibrium. However, the first baseline case (Zone 4 - Swansea) displays RH levels constantly above 80% throughout the year, once equilibrium is reached. 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 case is considered as 'fail', while the rest of the cases are considered as 'pass'.

The 80% RH threshold cannot be relaxed to 95% for this critical junction, as the following conditions are already present at this interface, in addition to high RH levels:

- air (in the unventilated air gap present at this interface)
- food for mould growth (with the existing plaster layer) and
- adequate temperature (as high RH levels are also reached during the summer period)

This means that all suitable conditions are met at this critical junction for mould growth to potentially occur.

These results are summarised in the table below.

Results

Table 39: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Fail	Case 5 Pass	Case 8 Pass	Case 11 Pass
Other	-	-	-	-

These findings are, to a certain extent, in line with current concerns as highlighted in BS 5250 (2011).

These results show that, despite the build-up not being exposed to wind-driven rain, interstitial condensation can form at the critical junction in high exposure zones. To avoid this problem, prescriptive guidance BS 5250 (2011), paragraph G.3.2.4, states that: *'to prevent this risk of interstitial condensation, an AVCL should be applied between the thermal insulation and the internal finish'*. However, the foil facing layer already present in the build-up is considered an AVCL, as the one-dimensional limitation of the modelling does not depict the fact that this foil layer is not continuous in practice. This proves that the recommendations currently listed in BS 5250 (2011) are incomplete.

However, these findings are not in line with current practice in the industry, as the use of internal wall insulation on an uninsulated cavity wall is considered a 'safe' retrofit measure in any locations / wind-exposure zones. This is due to the belief that the brick outer layer provides protection from direct wind-driven rain and solar gains to the wall build-up.

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 'fail', as these external conditions (external temperature and RH levels) lead to RH levels at the critical junction constantly remaining above the 80% threshold throughout the year.

17.3.5. Conclusions – Baseline

While the WUFI modelling results confirm the Glazer analysis is correct (with no interstitial condensation at the critical junction) and the cases in Zones 1, 2 and 3 are considered a 'pass', the build-up is considered a 'fail' in Zone 4. This means that the build-up is risky and likely requires further investigation and sensitivity testing to assess the robustness of the construction.

17.4. Sensitivity Analysis – Change in Material [Cases X.d]: Reduced insulation thickness

17.4.1. Sensitivity Analysis Cases

The baseline build-up fails for the Zone 4 - Swansea case, due to the generally higher external RH conditions, having a repercussion on the critical junction which is kept at a cold temperature by the addition of the IWI. Therefore, an additional sensitivity analysis is to reduce the thickness of the IWI layer applied to the blockwork. This is designed to worsen / increase the corresponding U-value in order to increase the temperature at the critical junction (thus reducing the corresponding relative humidity). This approach is recommended by some organisations to limit the impact of internal wall insulation retrofit on moisture issues. The thickness of insulation in this case is reduced from 78mm to 25mm (thinnest practically possible).

The sensitivity analysis case is only run for the one failing location, i.e. Zone 4 - Swansea, meeting a reduced U-value (as cases in other exposure zones are already considered as 'pass'):

Table 40: 1 sensitivity case

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	(baseline)	-	-	-
Reduced	Case 2.d	-	-	-
Other	-	-	-	-

17.4.2. Graphs at Critical Junction

All graphs 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.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4). The sensitivity analysis case is displayed as a coloured line, while its respective baseline case is displayed with a grey line.

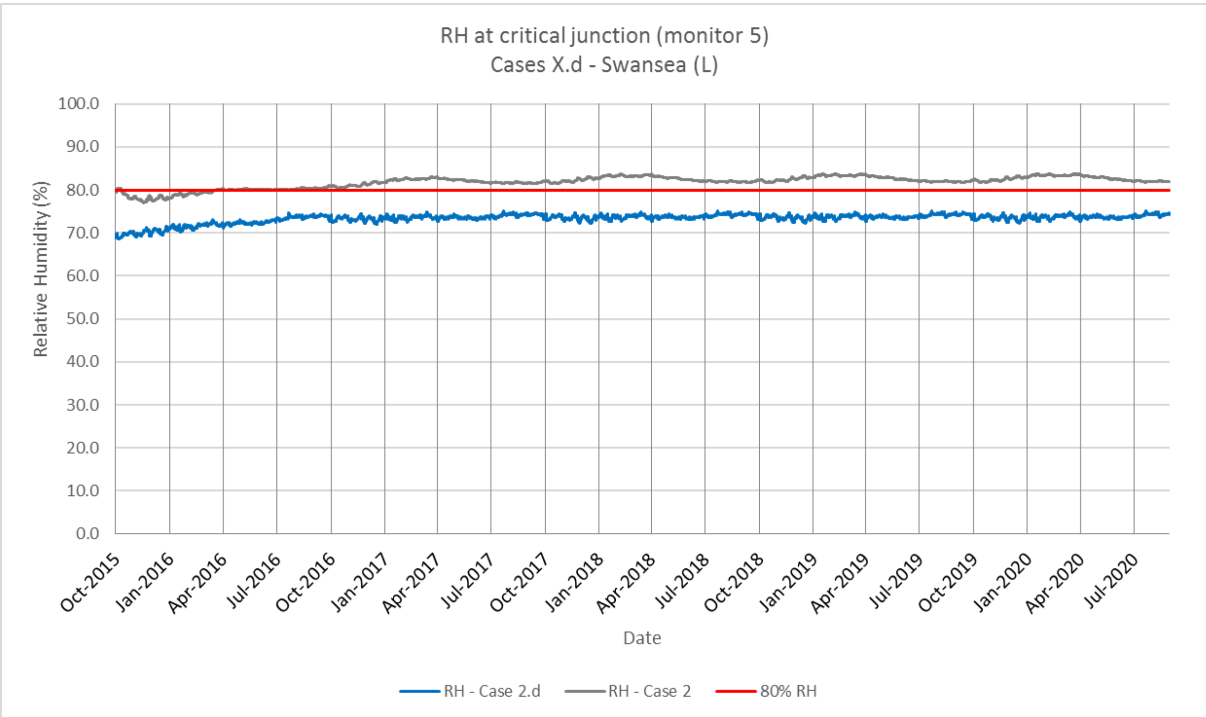


Figure 114: RH levels at critical junction for Cases 2 and 2.d

17.4.3. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

As expected, the reduction in insulation has a positive impact on the hygrothermal performance of the build-up, as the critical junction is kept at a slightly warmer temperature. As such, the Zone 4 - Swansea case, now passes in addition to the other cases, as the RH levels at the critical junction remain below the 80% RH threshold throughout the modelling period.

Results

The table below summarises the performance of the sensitivity analysis case:

Table 41: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	-	-	-	-
Reduced	Case 2.d Pass	-	-	-
Other	-	-	-	-

Impact of Insulation Thickness

The baseline and sensitivity analysis cases show that the installation of closed-cell insulation internally to an uninsulated cavity wall cannot be declared ‘safe’ in all exposure zones, as with the thick layer of insulation (in this case, 78mm), the case in Zone 4 – Swansea is considered as ‘fail’. However, the reduction of the insulation thickness improves the hygrothermal performance of the build-up, allowing it to be pass the risk criteria (in this case with a reduced insulation thickness of 25mm).

This means that there is a limiting value of internal wall insulation thickness to be retrofitted to ensure the build-up remains a ‘safe’ build-up in terms of moisture risks, with the limiting insulation thickness depending on the exposure zone the build-up is located in and the thermal conductivity of the insulation.

17.5. Conclusions

- BS EN ISO 13788 is considered adequate for analysis of this typology
- 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)
- Reduction in insulation thickness has a beneficial impact on the hygrothermal performance of the build-up. This means that a limiting insulation thickness exists in each specific case, above which the build-up cannot be considered ‘safe’ anymore (depending on exposure zone + insulation thermal conductivity)

18. Typology R11.2: Cavity masonry (uninsulated) Retrofit Measure: External Wall Insulation (EWI) and Cavity Wall Insulation (CWI)

The R11.2 typology is an uninsulated cavity wall prior to retrofit. The retrofit measure is to insulate the wall externally with closed-cell insulation as well as insulating the cavity with blown mineral wool.

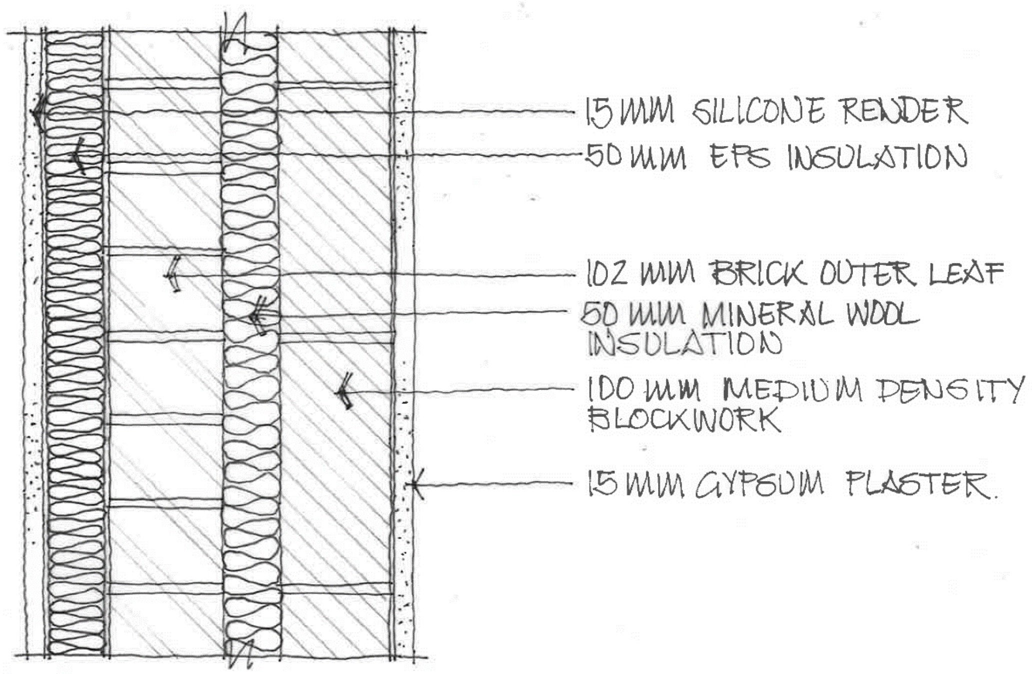


Figure 115: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

18.1. Assessment Method

The build-up contains porous materials having the capacity to store moisture, however, the porous material (cavity masonry wall)'s external surface is not directly exposed to the elements (rain, wind and radiations) due to additional layers installed externally to the cavity wall. Therefore, the BS EN ISO 13788 (2012) assessment method is valid for this typology, for the equilibrium state. Indeed, the fact that the insulation layers are added as a retrofit measure onto a potentially damp outer layer of the cavity wall means that in practice, the initial conditions differ from the default input data used in the BS EN ISO 13788 (2012) calculation.

Despite this difference in initial conditions, both BS EN ISO 13788 (2012) and WUFI modelling following BS EN 15026 (2007) should display similar results for the equilibrium state.

The analysis of this build-up with the Glaser method suggests the critical junction is the inner surface of the brick outer leaf adjacent to the cavity wall insulation. The results by the Glaser method show that this build-up is considered a 'safe' build-up, with the presence of interstitial condensation at the critical junction in winter, which then fully evaporates during summer. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

This construction is not specifically covered in BS 5250 (2011).

18.2. Build-up

18.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 102mm brick outer leaf (hand-formed)
- 75mm ventilated air gap
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster

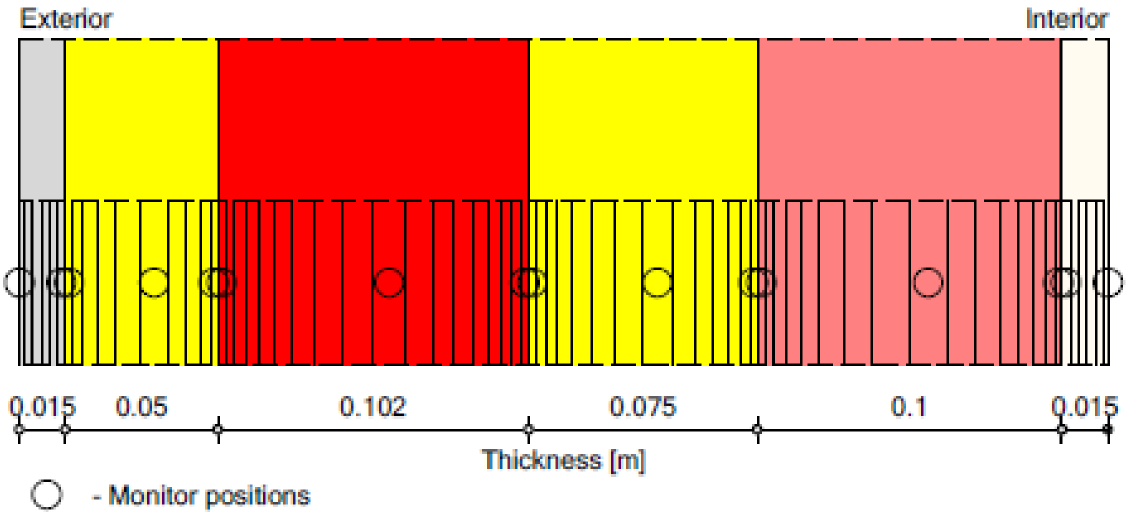
18.2.2. Initial Conditions

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.

18.2.3. WUFI Build-up (post-retrofit)

Build-Up:

- 15mm silicon render finishing coat
- 50mm EPS insulation (λ = 0.040 W/m.K)
- 102mm brick outer leaf (hand-formed)
- 75mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm gypsum plaster



Materials:

	- Silicon Resin Finishing Coat	0.015 m
	- EPS (heat cond.: 0.04 W/mK - density: 15 kg/m³)	0.05 m
	- 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

18.3. Baseline Results

18.3.1. Baseline Cases

The 8 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 42: 4 baseline cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

18.3.2. Critical Junction

For this typology, paragraph G.3.2.3 of BS 5250 (2011) on fully filled cavity walls states that: *'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)'*. Therefore, all graphs will display RH levels at this interface.

It is worth noting that properly installed external wall insulation should prevent the risks associated with "bridging" of the cavity due to imperfections in cavity construction, which is likely to worsen the performance of the build-up at the critical junction.

18.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the inner surface of brick outer leaf, adjacent to the cavity wall insulation.

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).

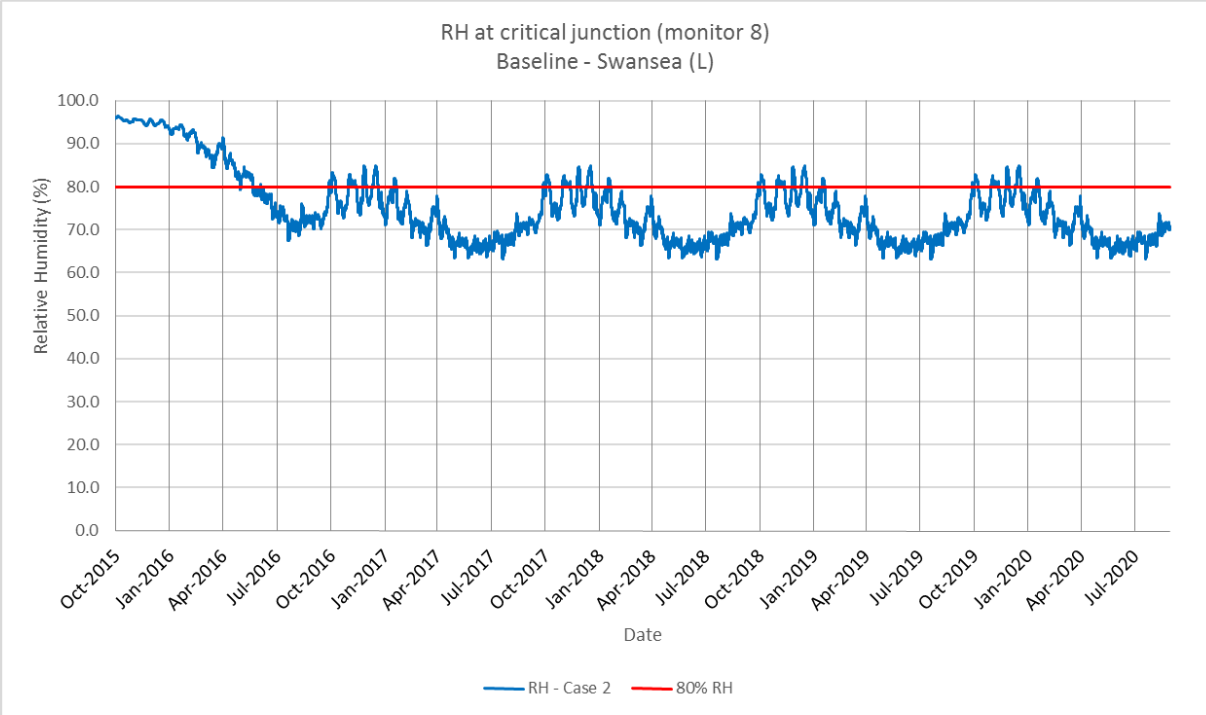


Figure 116: RH levels at critical junction for Case 2

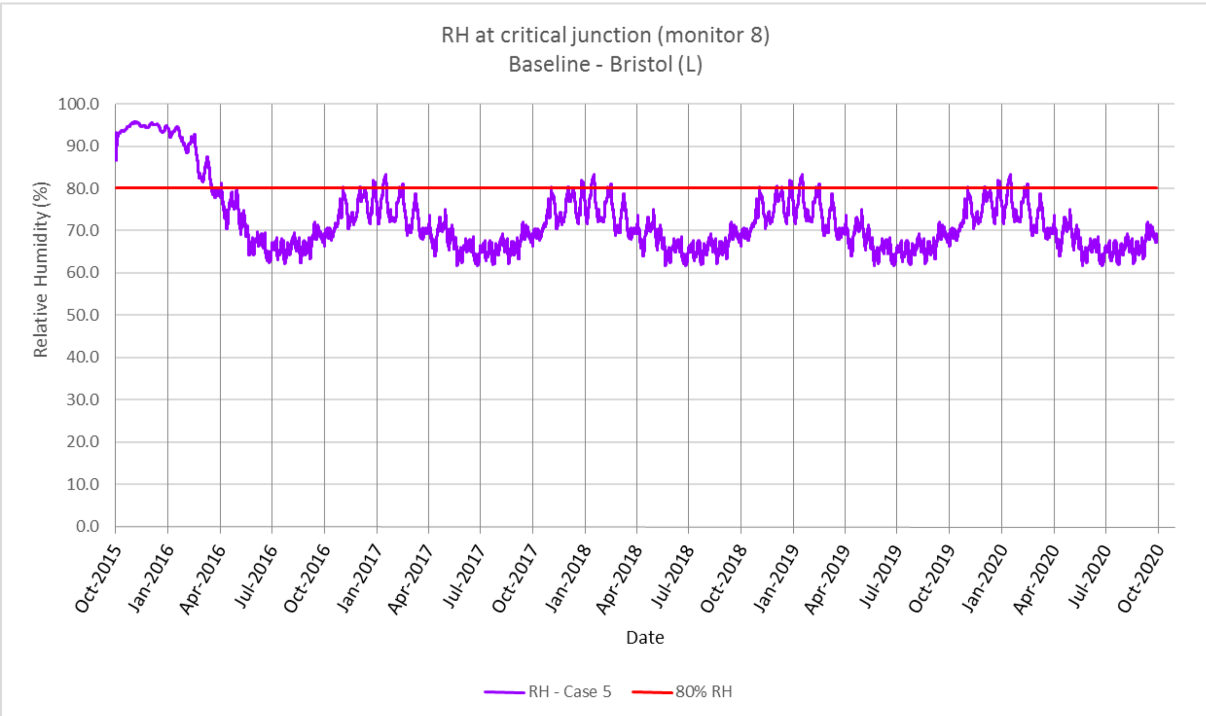


Figure 117: RH levels at critical junction for Case 5

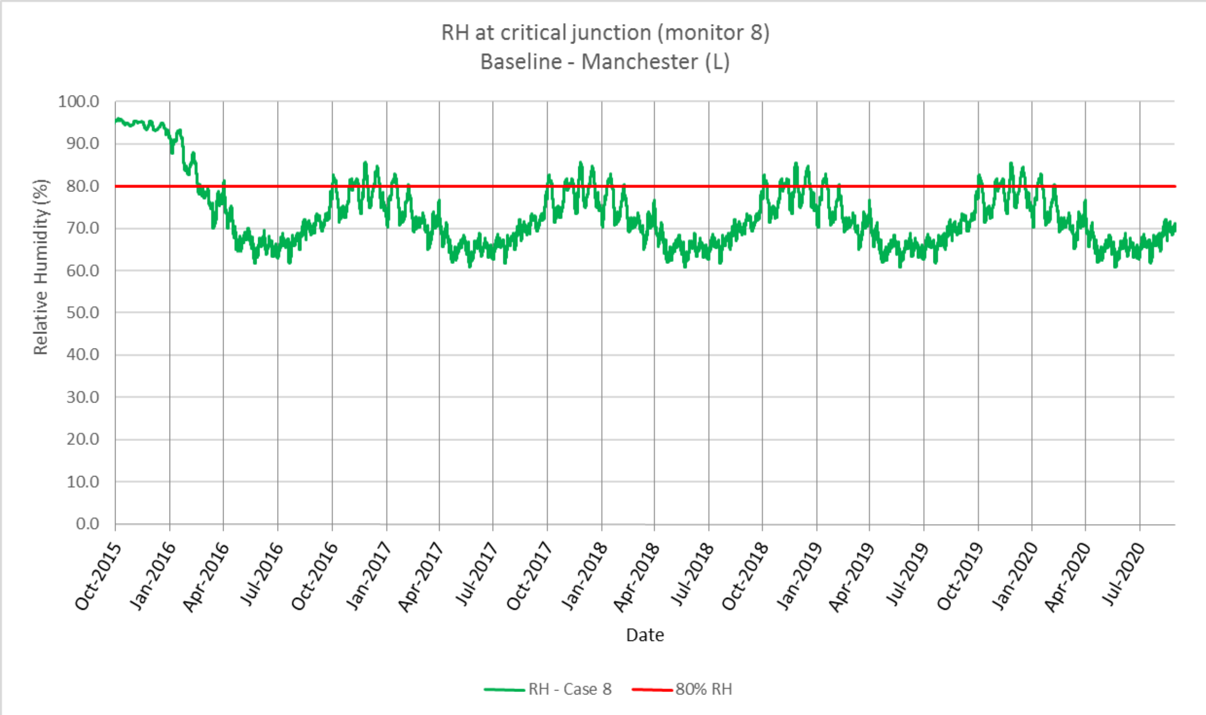


Figure 118: RH levels at critical junction for Case 8

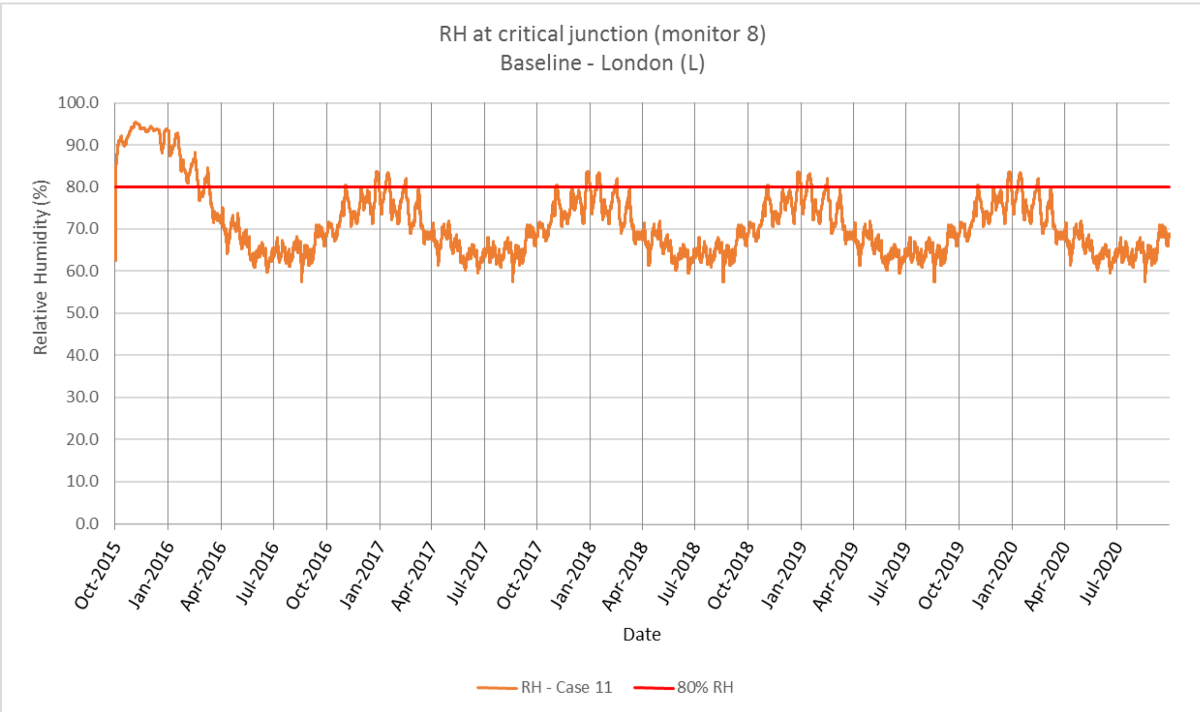


Figure 119: RH levels at critical junction for Case 11

18.3.4. Results Analysis

Moisture risk assessment criteria
All cases reach equilibrium after an initial period extending up to nine months of drying of the initially 'damp' outer brick leaf.

For this initial period, all cases display RH levels well above 80%. However, all the conditions for mould growth are not met at this interface as food for mould growth should also not be abundant at this interface. In addition, if mould growth was to occur, as its location is isolated from the indoor environment, there would be no significant consequences to the health of building's occupants.

The initial drying-up period extends longer than six months for the Zone 4 - Swansea case, making this case listed as 'risky' compared to the three other cases (in which this period is below six months, meaning these cases 'pass'). When equilibrium is then reached, each case displays the following:

- RH levels mostly retain below the 80% threshold for most of the year
- RH levels peak above 80% only intermittently

However, these peaks are very short in time (much shorter than a month), which means that they do not have a detrimental impact on the hygrothermal performance of the build-up.

These results are summarised in the table below.

Results

Table 43: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Risky	Case 5 Pass	Case 8 Pass	Case 11 Pass
Other	-	-	-	-

The critical junction is correctly located in the BS EN ISO 1388 (2012) calculations. However, these modelling results differ from the BS EN ISO 13788 (2012) calculations, as despite higher RH levels being present at the critical junction in winter, no interstitial condensation is present throughout the year.

Effects of exposure zones

The difference in exposure zones is only just noticeable on the graphs, with minor differences between the build-up in zones that are more or less exposed to wind-driven rain. This finding is as predicted, since the rendered external wall insulation isolates the brick outer leaf from external conditions.
The only major difference visible due to different exposure zones is the length it takes for the initial RH levels to go below the 80% RH threshold. The more exposed

the zone is, the longer the period of high initial RH levels (with the conditions experienced in Zone 4 – Swansea being classified as 'risky', rather than 'pass').

18.4. Conclusions

- This typology is mainly considered 'safe' as there was no interstitial condensation at the critical junction, though the exposure zone impacted on initial drying period (which can put the build-up more at risk)
- BS EN ISO 13788 does not appear adequate for analysis of this typology
- Risk of mould growth not considered highly significant (due to lack of abundant food and location of critical junction in the cavity).
- However, possibility for 'non-perfect' build-up in practice (ABIS conditions), which could mean additional moisture as results likely depend on good installation of both CWI & EWI to prevent moisture ingress and localised cold areas (e.g. around windows)
- Build up not specifically covered in STBA/DECC Moisture Risk Assessment and Guidance document (2014) or BS 5250 (2011), though build-up likely to be common in retrofit

19. Typology R11.3: Partial-fill cavity masonry Retrofit Measure: Internal 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).

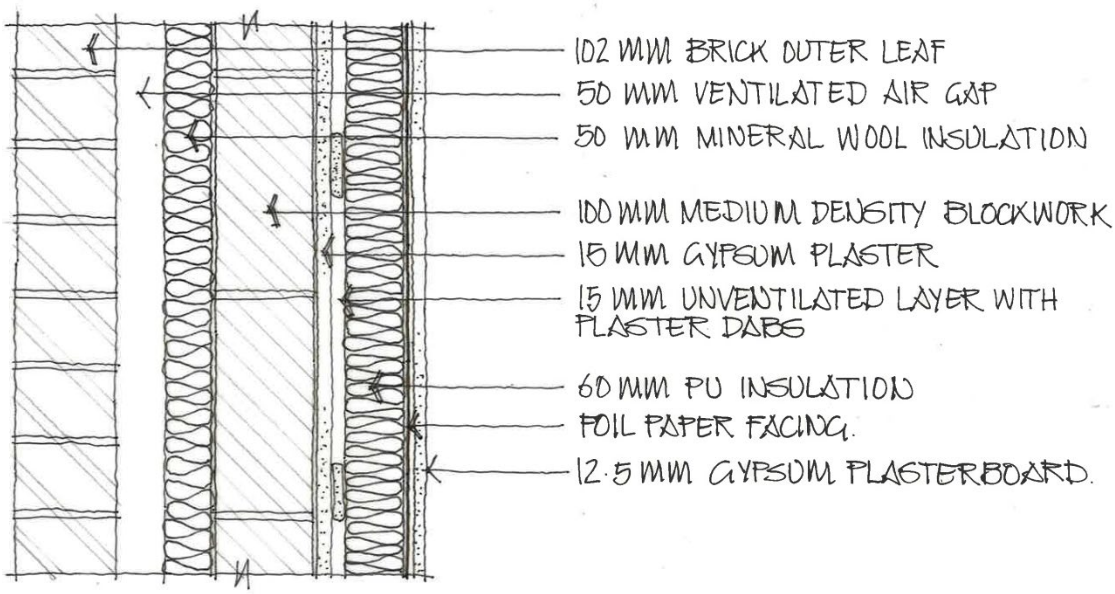


Figure 120: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

19.1. Assessment Method

As BS 5250 (2011) states in the cavity wall section (paragraph G.3.2.1), *'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.'*

As per the similar new build construction N11, 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). Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method. The results by the Glaser method show that this build-up is generally considered to be a 'safe' build-up, with the lack of interstitial condensation at all interfaces throughout the year. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

19.2. Build-up

19.2.1. 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

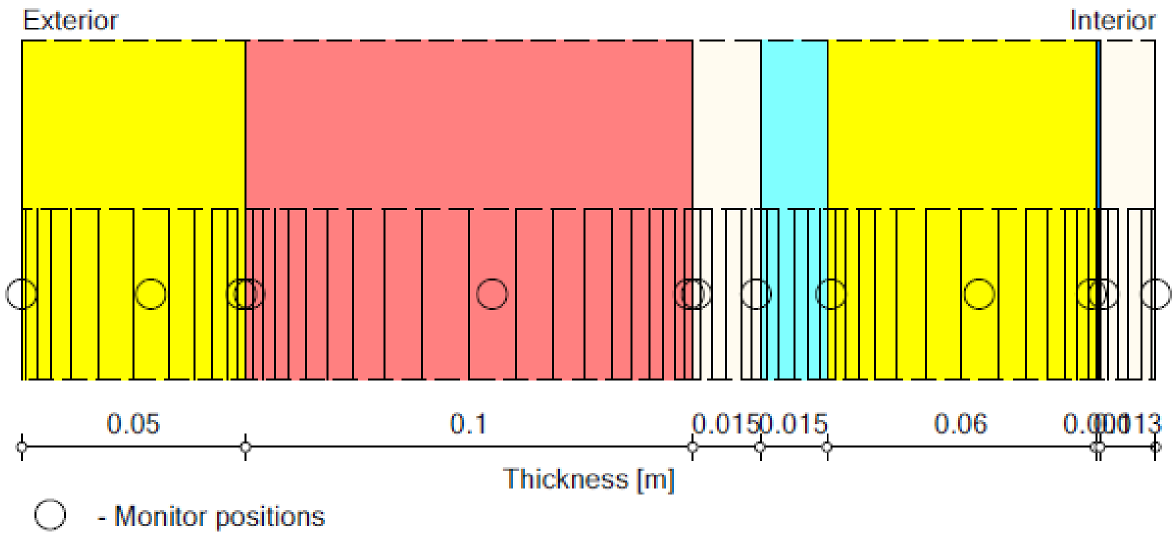
19.2.2. Initial Conditions

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.

19.2.3. WUFI Build-up (post-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
- 15mm unventilated air gap with plaster dabs
- 60mm PU insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 12.5mm gypsum plasterboard



Materials:

	- *Mineral Wool (heat cond.: 0,04 W/mK)	0.05 m
	- *Medium density blockwork	0.1 m
	- Interior Plaster (Gypsum Plaster)	0.015 m
	- *Air Layer 15 mm; without additional moisture capacity (unlocked)	0.015 m
	- *PU (heat cond.: 0,025 W/mK)	0.06 m
	- *Foil paper facing (sd = 14m) (unlocked)	0.001 m
	- *Gypsum Board (unlocked)	0.013 m

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 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

19.3. Baseline Results

19.3.1. Baseline Cases

The 8 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 44: 4 baseline cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

19.3.2. 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.3.2.4 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'*.

19.3.3. 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).

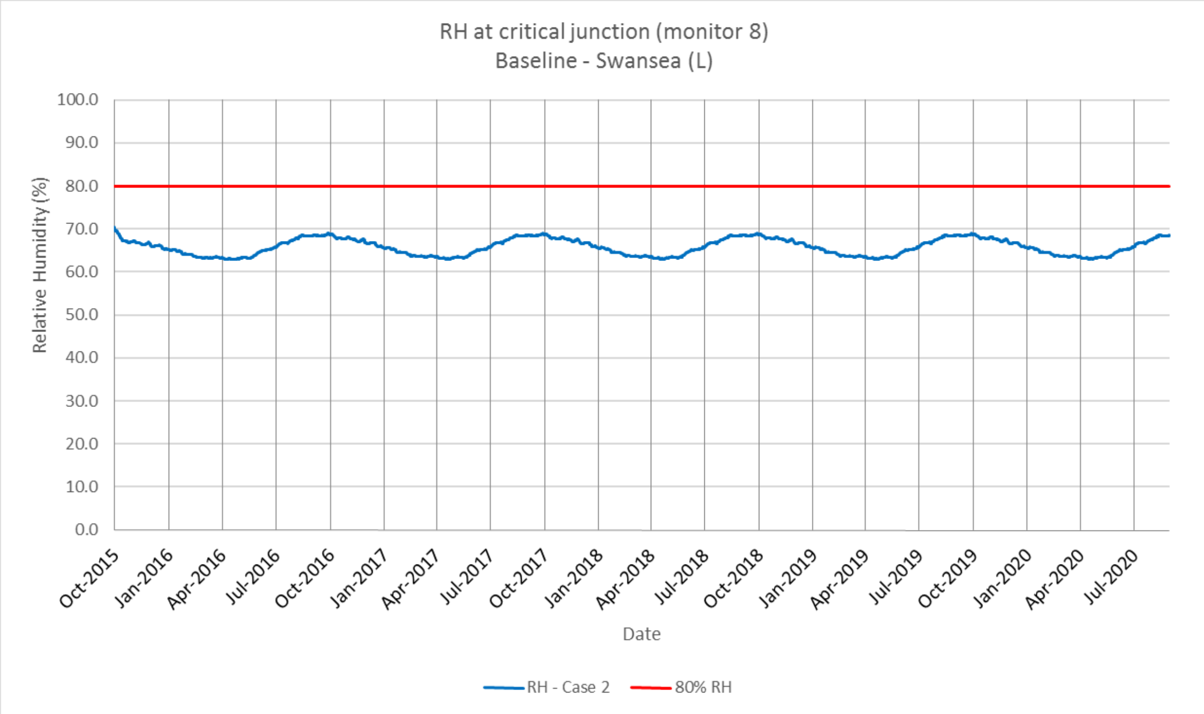


Figure 121: RH levels at critical junction for Case 2

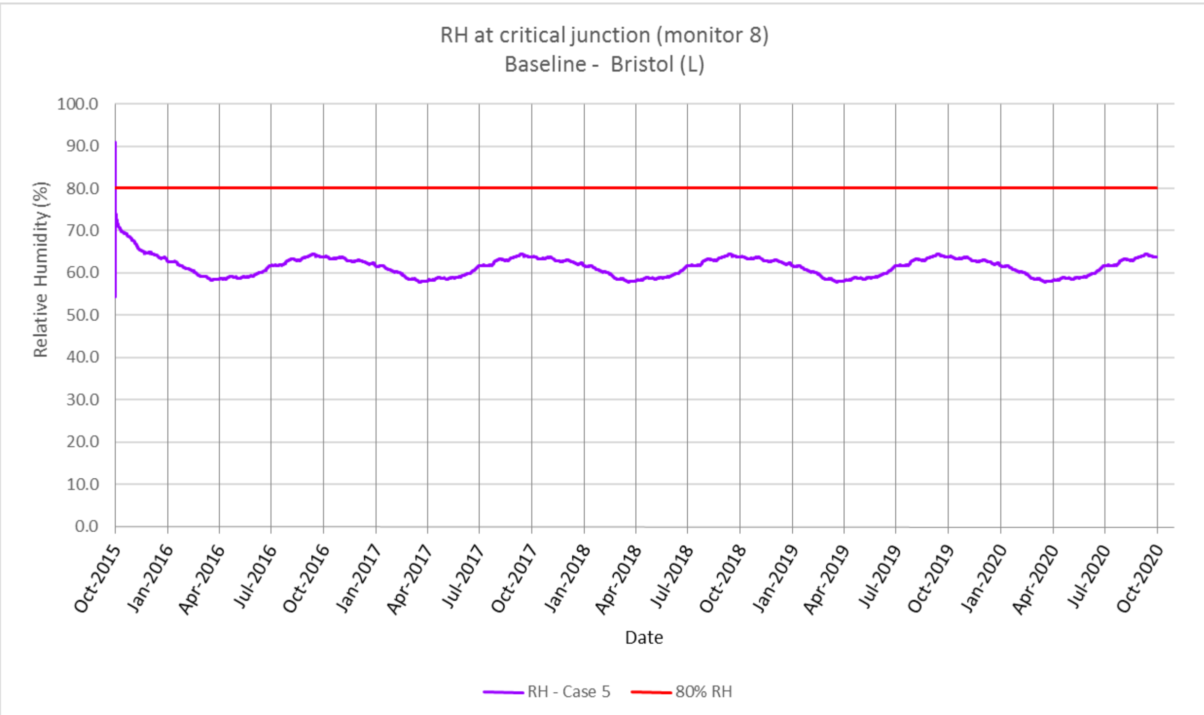


Figure 122: RH levels at critical junction for Case 5

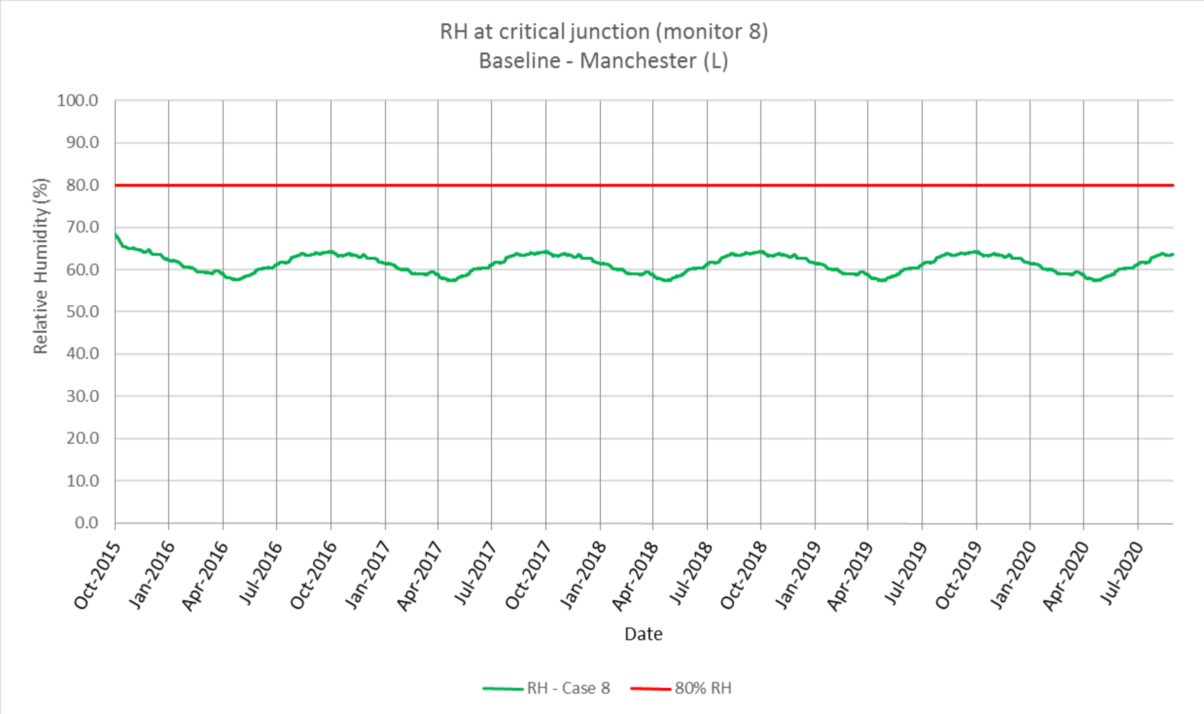


Figure 123: RH levels at critical junction for Case 8

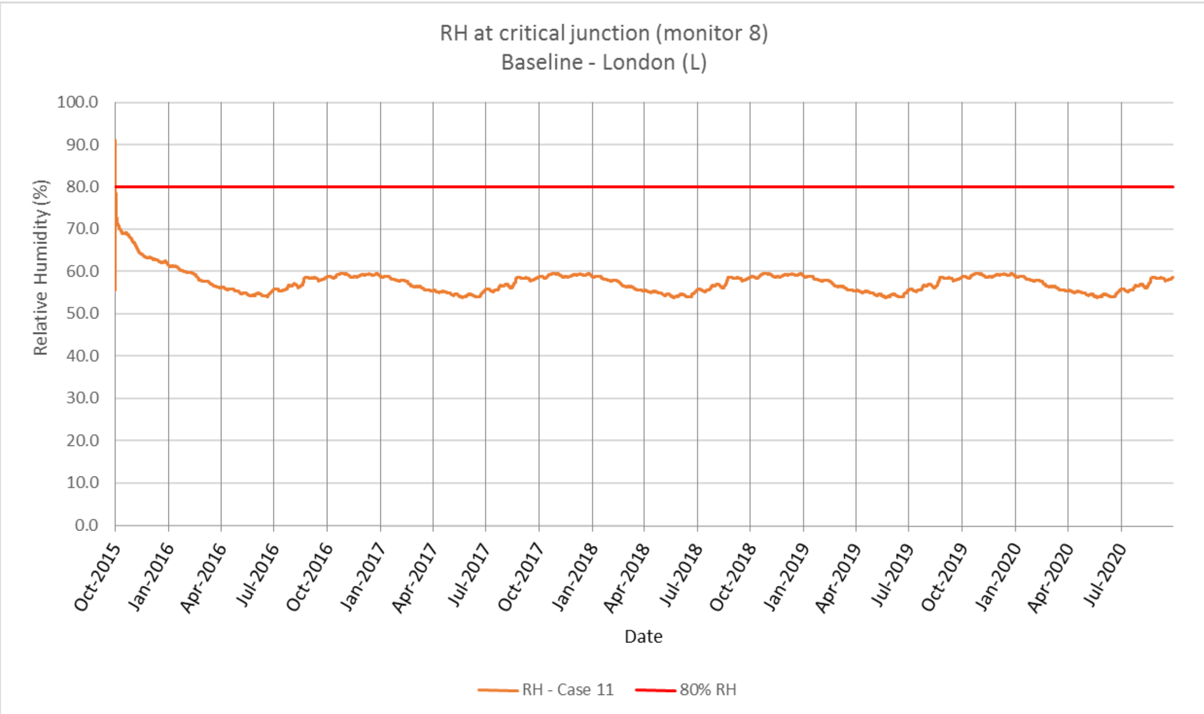


Figure 124: RH levels at critical junction for Case 11

19.3.4. Results Analysis

Moisture risk assessment criteria

As seen with the BS EN ISO 13788 (2012) calculations, all scenarios are 'pass' as they all reach equilibrium, do not accumulate moisture over time and have RH levels well below 80%. In addition, the initial conditions are only slightly visible on the graphs and do not have any major impact on the RH levels at the critical junction. This is as predicted, as the inner medium density blockwork is not exposed to wind-driven rain and therefore does not present initial conditions with relatively high moisture content.

These results are summarised in the table below.

Results

Table 45: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
Other	-	-	-	-

These results are in line with the BS EN ISO 13788 (2012) calculations, as both methods show the lack of interstitial condensation at the critical junction throughout the year.

Effects of exposure zones

The effect of wind-driven rain exposure zones is slightly visible on the graphs – with lower average RH levels in less exposed zones. However, this is directly due to different external (and consequently internal) conditions. This difference in exposure zones does not have an impact on the hygrothermal performance of the build-up and the status of each case, as the modelled build-up is sheltered from direct wind-driven rain.

19.3.5. Additional Monitored Junction

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

A second interface, which is less at risk but where there might still be a risk for moisture to accumulate, is the interface between the cavity wall insulation and the outer surface of the inner blockwork wall leaf. As such, the results from this additional monitor, on the inner surface of the cavity wall insulation, are examined to get a clearer picture of the hygrothermal performance of the whole build-up.

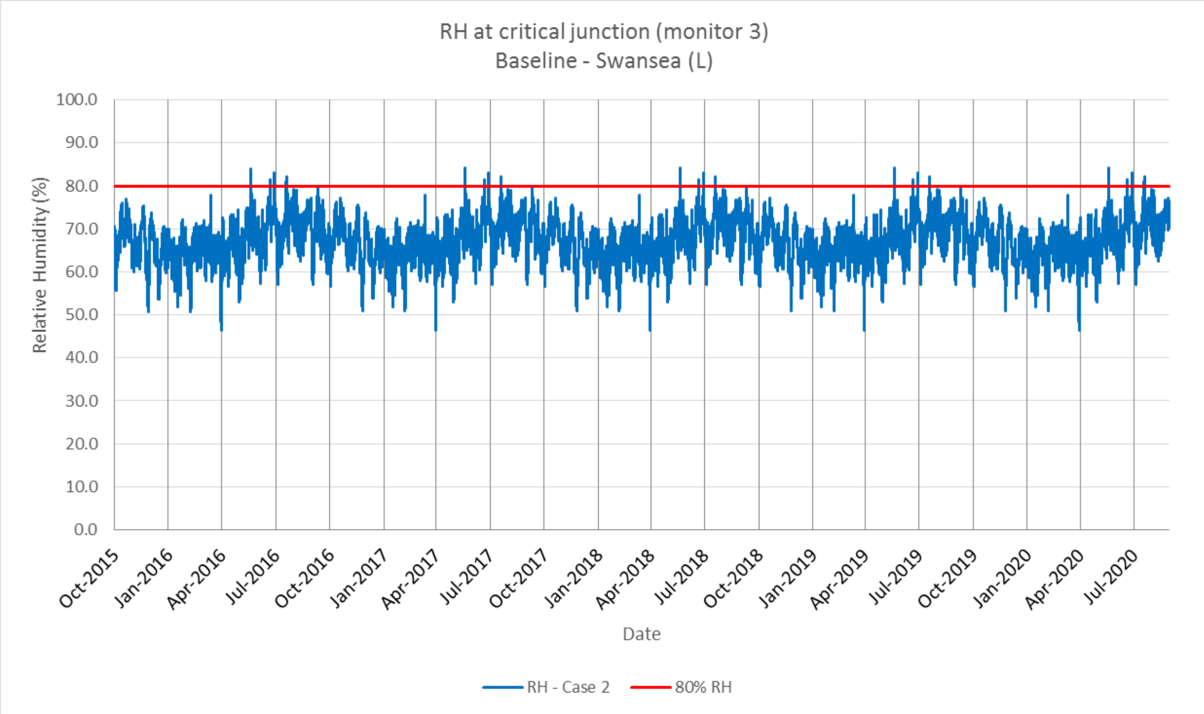


Figure 125: RH levels at additional monitored junction for Case 2

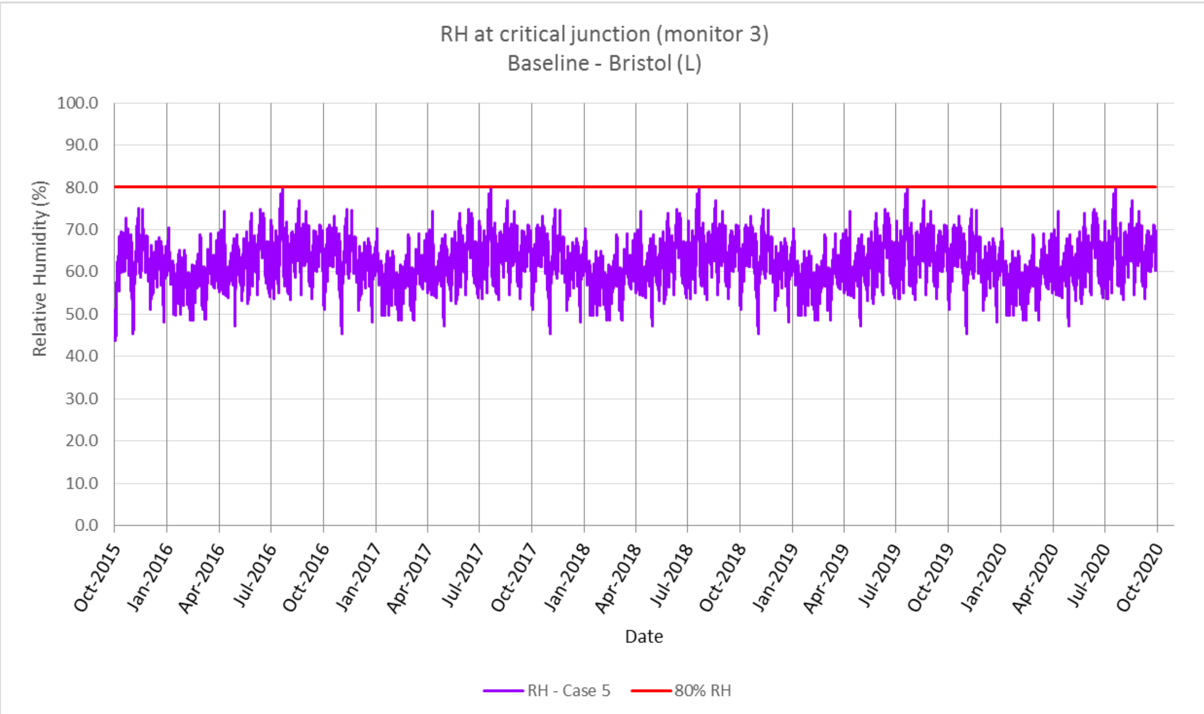


Figure 126: RH levels at additional monitored junction for Case 5

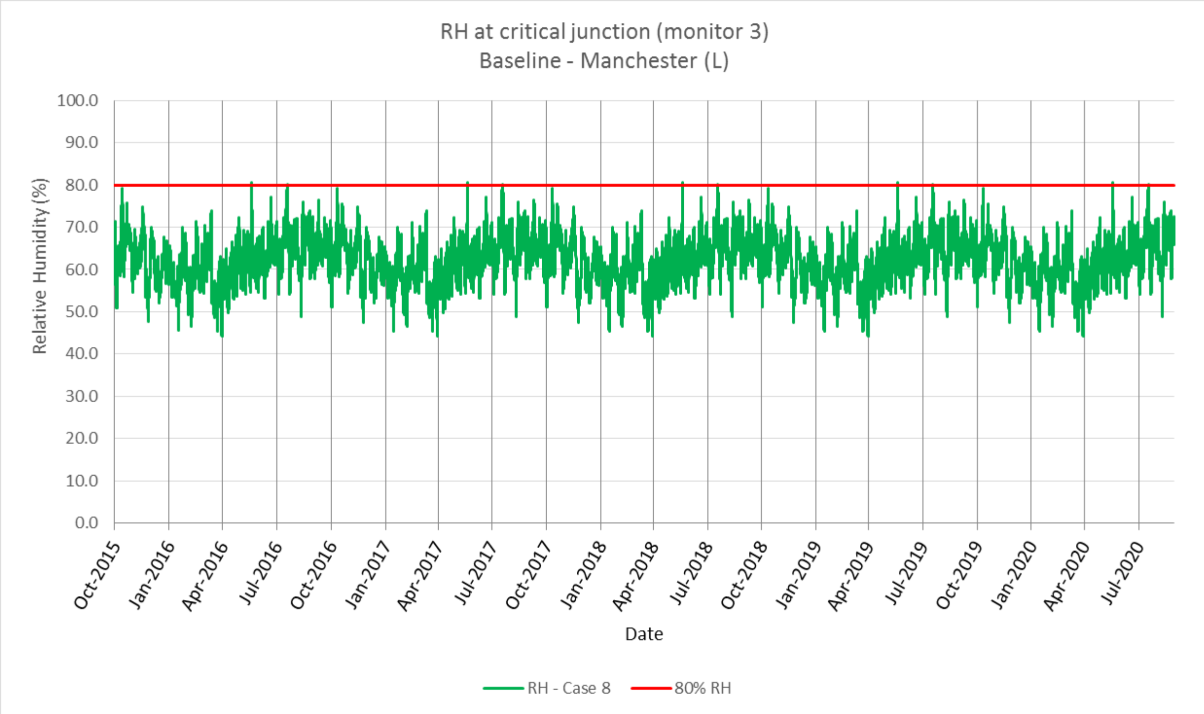


Figure 127: RH levels at additional monitored junction for Case 8

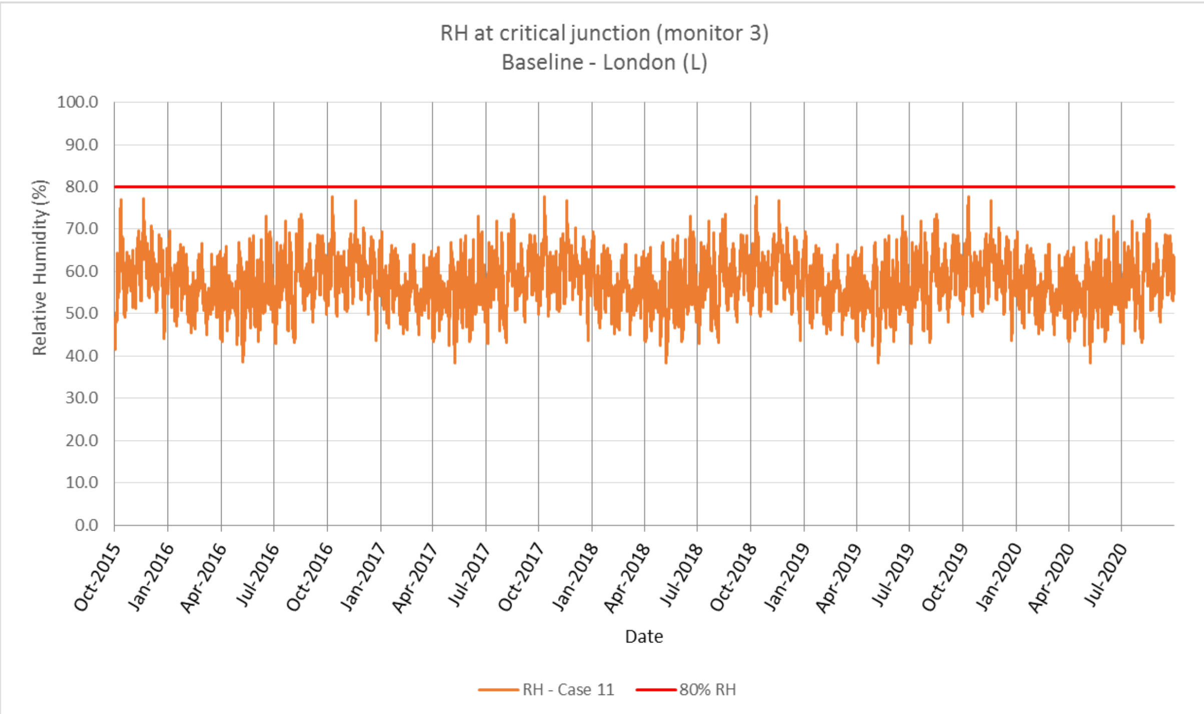


Figure 128: RH levels at additional monitored junction for Case 11

These graphs are in line with the previous findings, and confirm the previous results. Indeed, all cases reach equilibrium, do not accumulate moisture over time and have RH levels well below 80%.

19.4. Conclusions

- This build-up is sheltered from the elements and moisture-open so theoretically safe
- Safe results similar to 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

20. Typology R12: Full-fill cavity masonry Retrofit Measure: Internal 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 wall insulation (IWI).

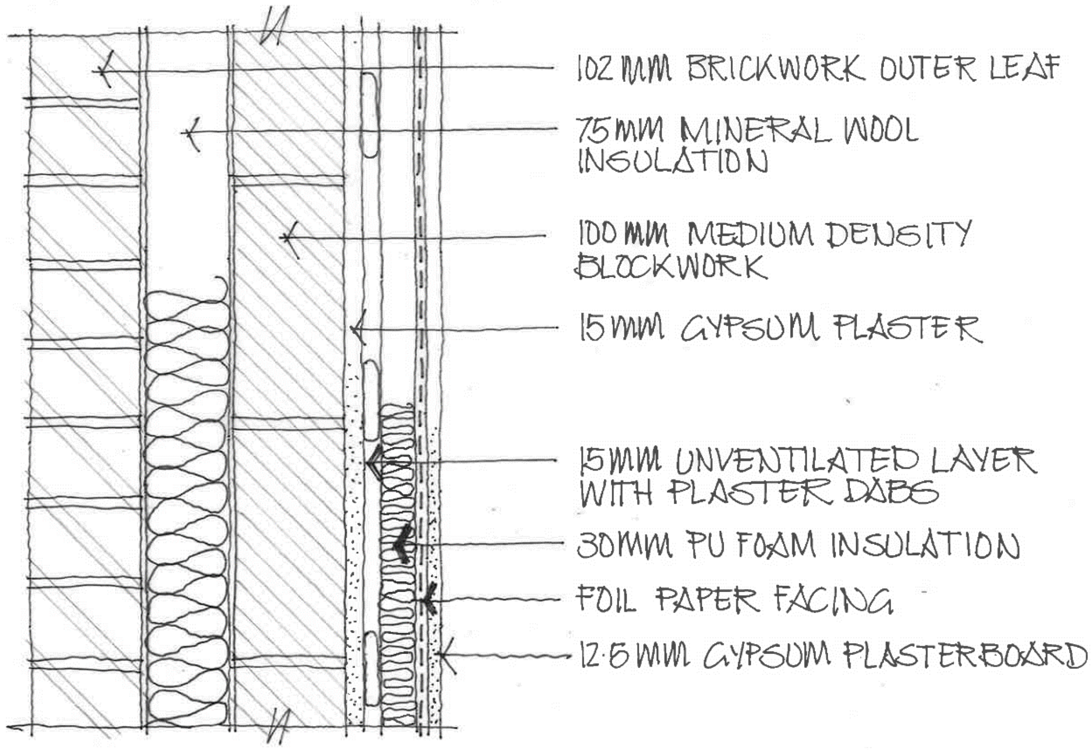


Figure 129: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

20.1. 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. Indeed, the results by the Glaser method show that this build-up is considered a ‘safe’ build-up, with no risk of interstitial condensation (which contradicts the WUFI modelling results).

Due to the limitations of previous methods to assess accurately the hygrothermal performance of this build-up, this typology will be assessed with the BS EN 15026 (2007) assessment method using WUFI modelling.

20.2. Build-up

20.2.1. 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

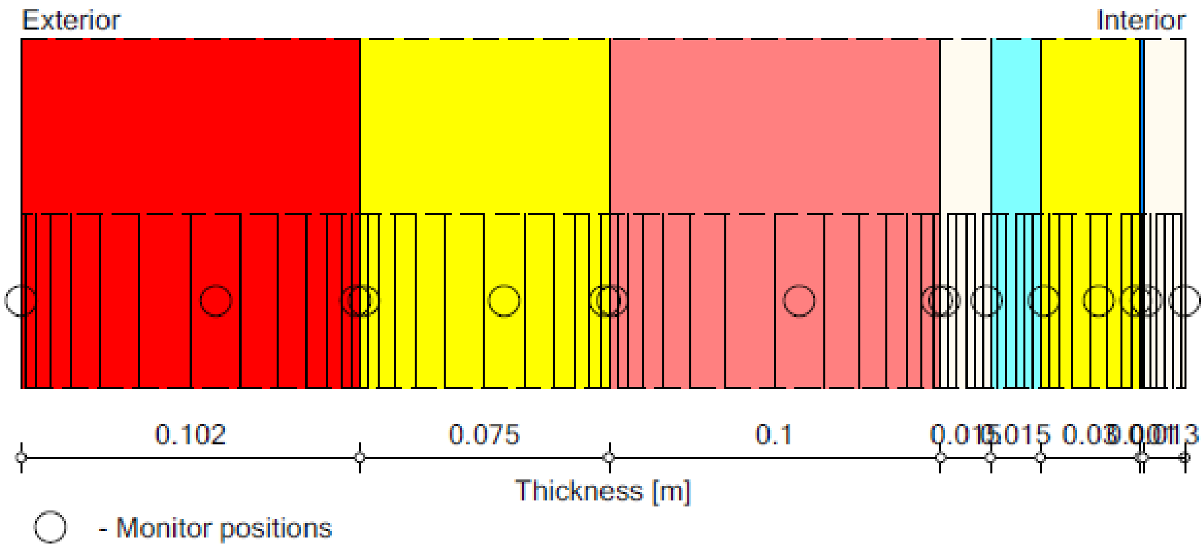
20.2.2. Initial Conditions

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.

20.2.3. WUFI Build-up (post-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
- 15mm unventilated layer with plaster dabs
- 30mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 12.5mm gypsum plasterboard



Materials:

(red)	- Solid Brick, hand-formed	0.102 m
(yellow)	- *Mineral Wool (heat cond.: 0,04 W/mK)	0.075 m
(pink)	- *Blockwork - medium density	0.1 m
(off-white)	- Interior Plaster (Gypsum Plaster)	0.015 m
(cyan)	- *Air Layer 15 mm; without additional moisture capacity	0.015 m
(yellow)	- *PU (heat cond.: 0,025 W/mK)	0.03 m
(blue)	- *Foil paper facing (sd = 14m) (unlocked)	0.001 m
(off-white)	- Gypsum Board	0.013 m

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. 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.

Sensitivity Analysis

As the brick’s physical characteristics play a significant role in the hygrothermal performance of this build-up, in addition to the lack of data available for UK bricks, the first sensitivity analysis is carried out with a substitution of the default bricks by two additional bricks with different physical characteristics (density, porosity and water absorption coefficient), described in section 20.4.1.

20.3. Baseline Results

20.3.1. Baseline Cases

The 8 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 46: 4 baseline cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

20.3.2. Critical / Monitored Junction

Prescriptive guidance for fully filled cavity walls in BS 5250 (2011) states that *'applying thermal insulation within a wall cavity risks compromising the primary function of the cavity, namely the avoidance of rainwater penetration.'* This shows that the build-up is likely to be prone to moisture risks.

The critical junction is correctly identified by the BS EN ISO 13788 (2012) calculation, also by BS 5250 (2011): *'any interstitial condensation which might occur will do so on the inner surface of the external skin'.* Therefore, all graphs will display RH levels at the interface between the brick outer layer and the cold side of the cavity wall insulation layer.

There is an additional location of concern at the interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation. This is in line with BS 5250 (2011) paragraph G.3.2.4 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'*.

20.3.3. Graphs at Critical Junctions

The graphs displayed below show the RH levels for each location at the two critical / monitored junctions:

- The interface between the inner face of the outer brick layer and the cold side of the cavity wall insulation (listed as monitor 3 here)
- The interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation (listed as monitor 11)

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).

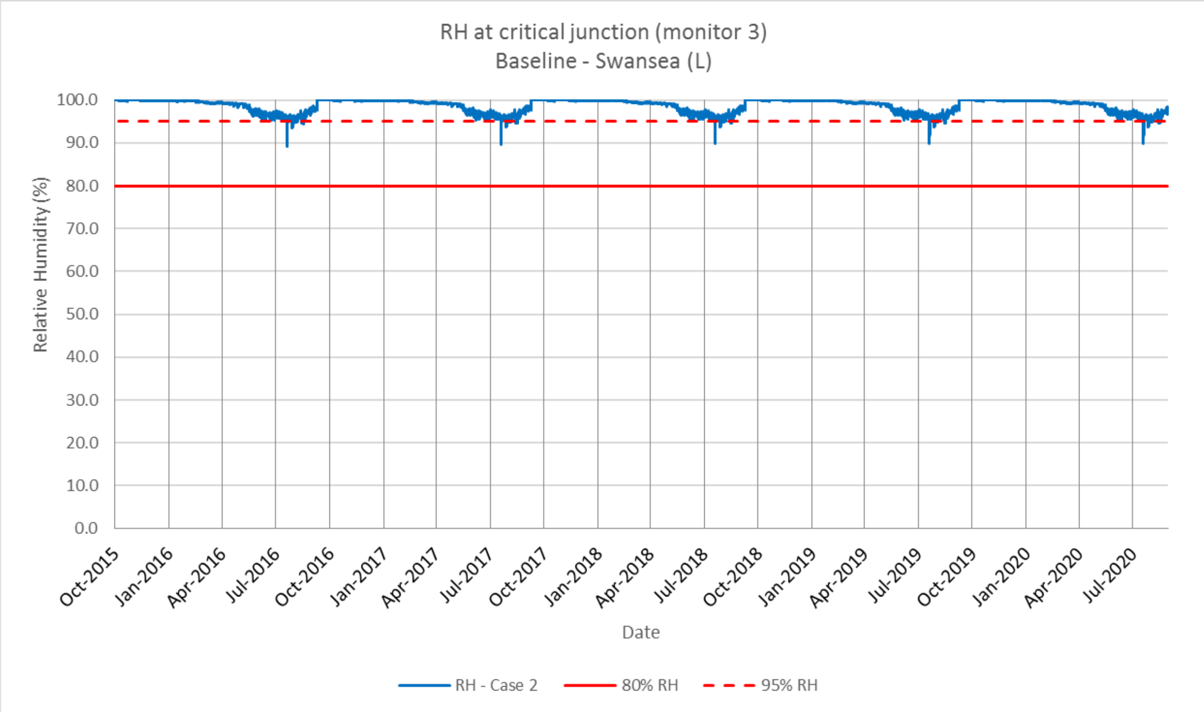


Figure 130: RH levels at critical junction (monitor 3) for Case 2

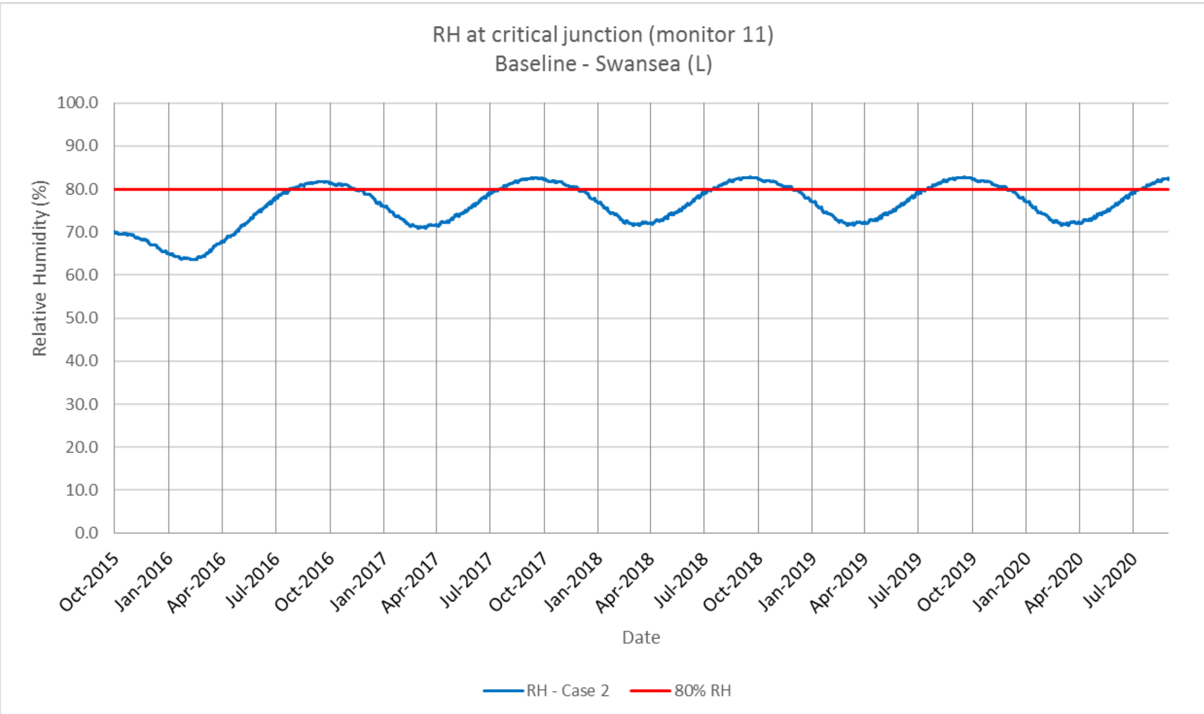


Figure 131: RH levels at critical junction (monitor 11) for Case 2

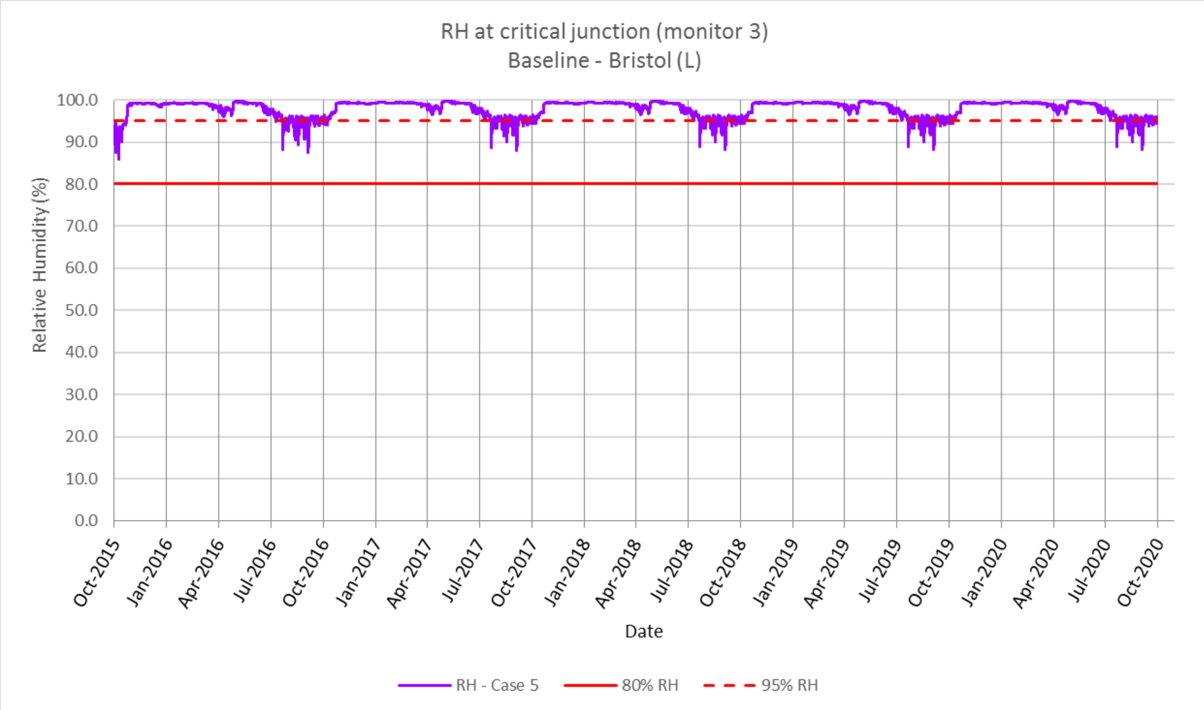


Figure 132: RH levels at critical junction (monitor 3) for Case 5

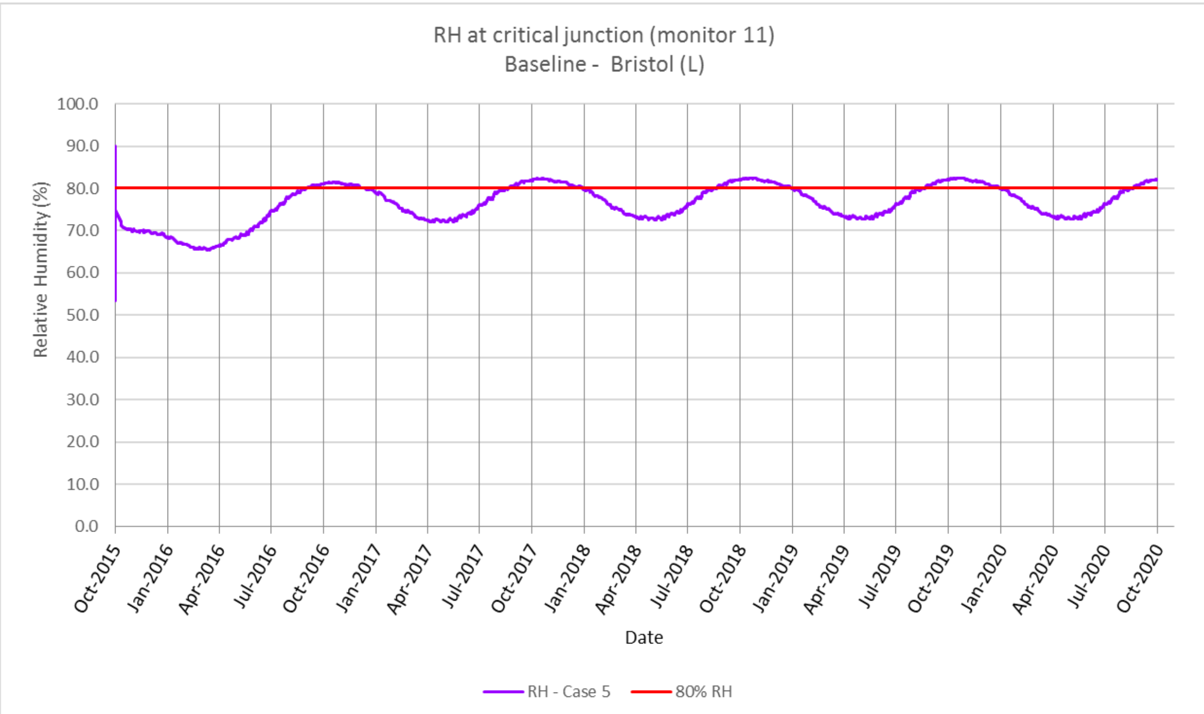


Figure 133: RH levels at critical junction (monitor 11) for Case 5

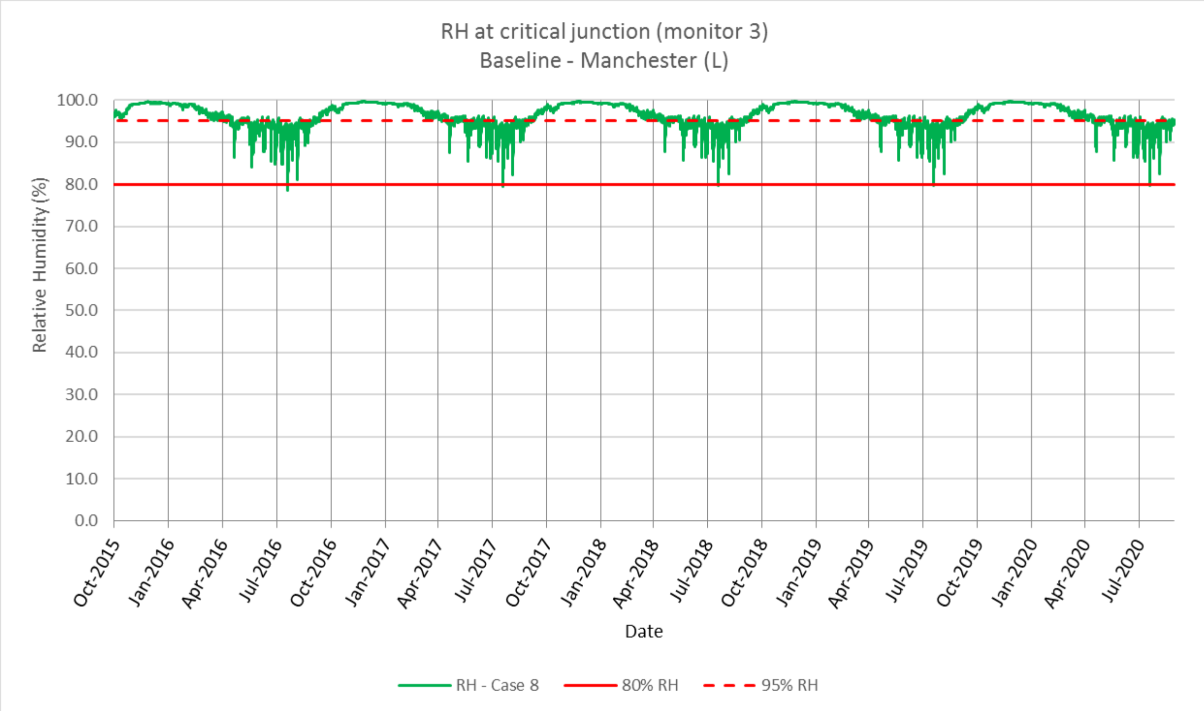


Figure 134: RH levels at critical junction (monitor 3) for Case 8

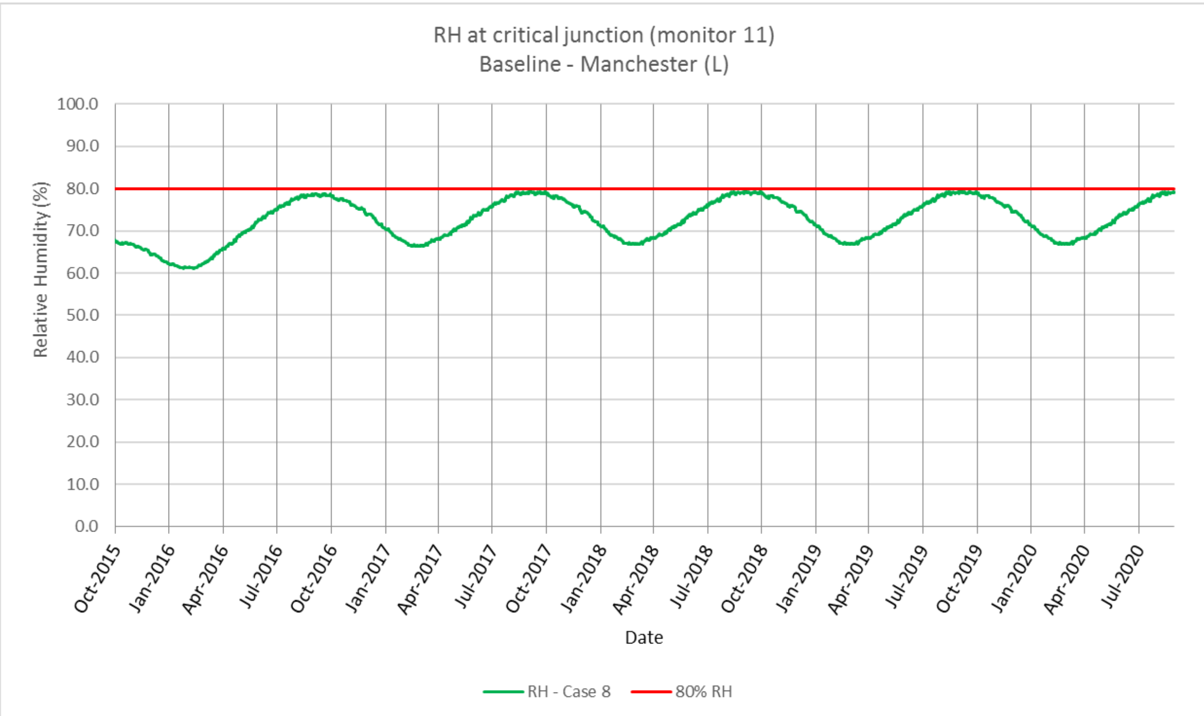


Figure 135: RH levels at critical junction (monitor 11) for Case 8

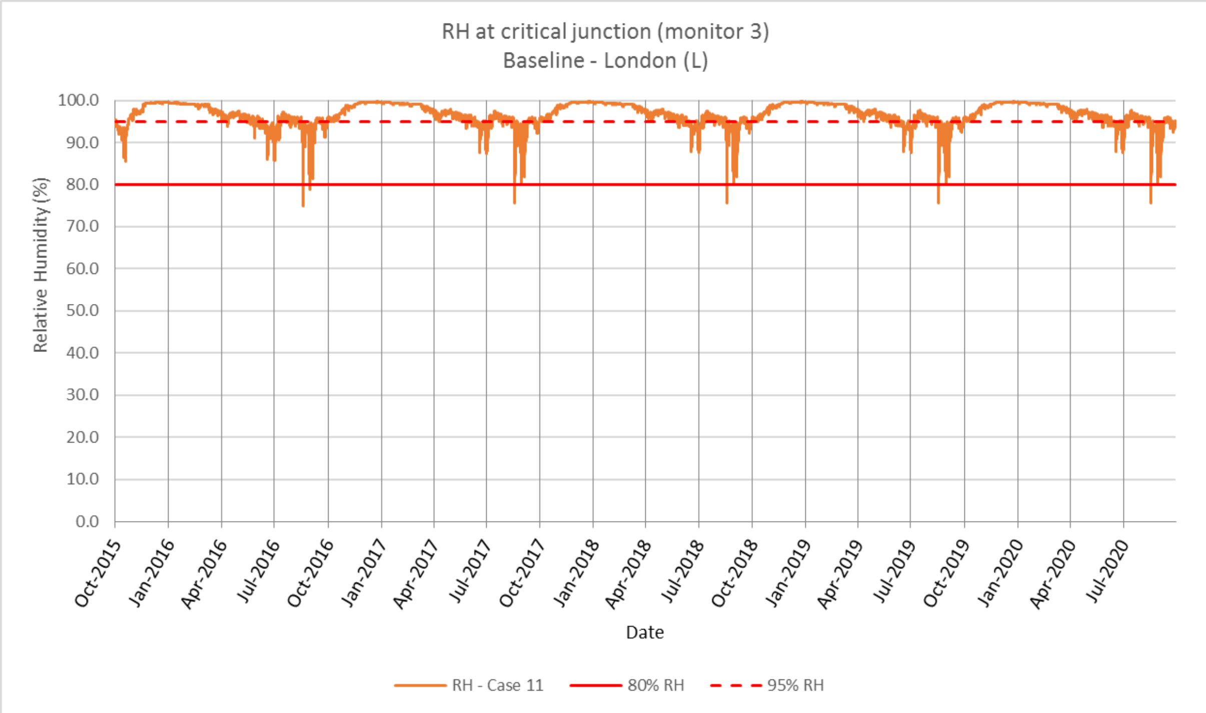


Figure 136: RH levels at critical junction (monitor 3) for Case 11

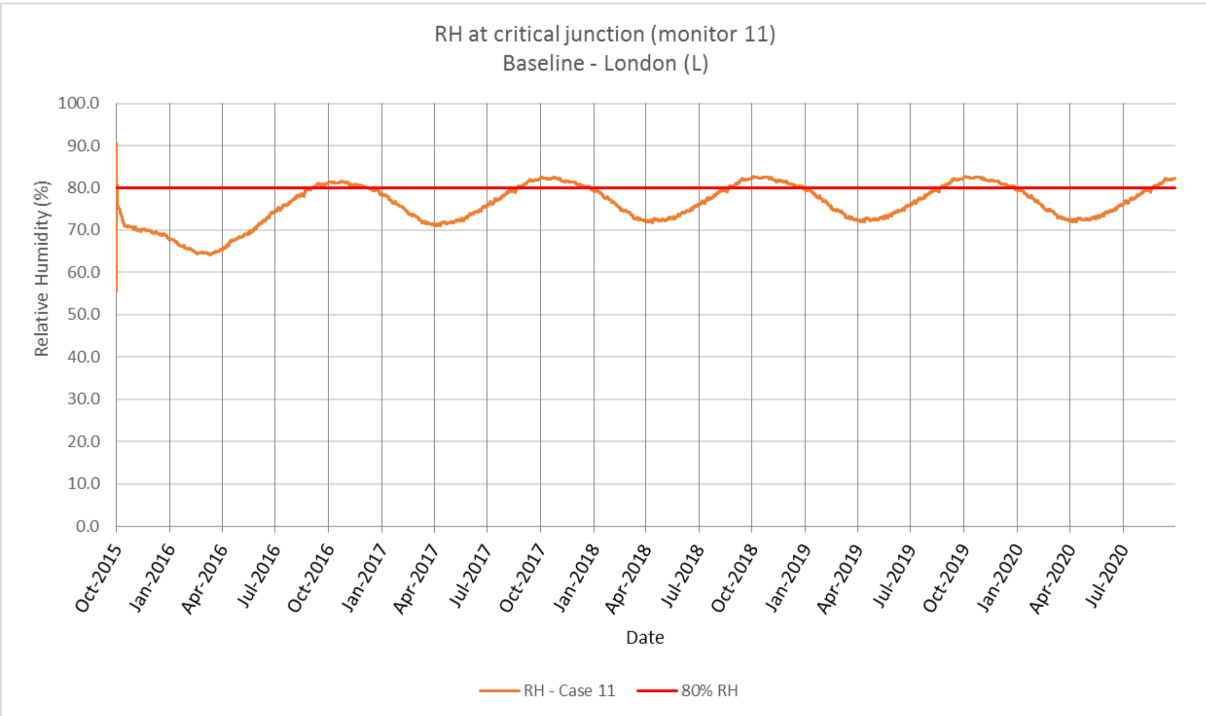


Figure 137: RH levels at critical junction (monitor 11) for Case 11

20.3.4. Results Analysis

Moisture risk assessment criteria

The moisture risk assessment criterion is normally set at 80% for the upper RH limit. This is maintained for the monitored junction between the inner leaf and the internal wall insulation (monitor 11), due to the presence of 'fragile' material at this interface (gypsum plaster). However, for the junction at the interface of the outer brick leaf and the cavity wall insulation (monitor 3), this criterion can be relaxed from 80% to 95%, as there is no significant food for mould growth and the interface is not within the occupied space (there is a blockwork wall sealing off the interior).

Interface: Outer Brick Leaf – Cavity Wall Insulation

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 the most extreme exposure zones (Zones 3 and 4).

As mentioned before, the risk was highlighted in paragraph G.3.2.3 in BS 5250 (2011) but the guidance also mentions that it should not lead to any damages, stating that: *'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'.* Therefore, this implies that high RH levels should not lead to moisture damages if 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).

However, this also raises the question (similarly to the N12 typology) of the actual thermal performance of the outer part of the insulation layer, which is exposed to very high RH levels. Indeed, mineral wool, like some other full-filled cavity wall insulation materials, has a moisture-dependent thermal conductivity.

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 N12 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.

However, if mould growth was 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.

Interface: Inner Blockwork Leaf – Internal Wall Insulation

Most cases show high RH at this second critical junction, with most cases exceeding the 80% RH threshold for periods up to several months a year, meaning there is a risk of mould growth. As most cases are considered a ‘fail’, except for the case in Zone 2 (Manchester) being considered ‘risky’ as the RH levels reach the 80% threshold but do not go over it.

Results

These results are summarised in the table below.

Table 47: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Fail	Case 5 Fail	Case 8 Risky	Case 11 Fail
Other	-	-	-	-

Effects of exposure zones

The difference in exposure zones is visually noticeable on the graphs, as they clearly 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 during which interstitial condensation occurs. This finding is as predicted, since the hygrothermal performance of exposed brick walls is directly affected by the external conditions.

It is also worth noting that best performing build-up is the build-up is Zone 2 (Manchester). This is due to the fact that the RH levels at that junction are subject to reverse condensation, with solar gains on the South-West façade pushing internally any moisture present in the build-up, therefore accumulating at this junction. Indeed, RH peaks occur around August – September period. As Manchester is the location receiving the least amount of solar gains out of the four locations, this problem is therefore less visible on the graphs, compared to the other zones.

Risk of Mould Growth (interface between inner blockwork and IWI)

Interstitial condensation is not a risk at the interface of the IWI and the inner leaf of the cavity wall, as the graph shows that RH levels are kept below 90%. However, the risk of mould growth is higher at this interface, as RH levels are kept above 80% during summer, with temperatures being adequate for mould growth. The presence of gypsum plaster also favours mould growth. And despite the lack of air at this interface in theory, it is possible for air to be present in practice.

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 (see section 20.4).

20.3.5. Conclusions – Baseline

- Due to the limitations of BS EN ISO 13788 and because the build-up has porous materials exposed to the elements (wind-driven rain + solar gains), then there is a need for the use of the BS EN 15026 assessment method
- The hygrothermal performance of this build-up is linked to the 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
- There was the presence of interstitial condensation, though not a significant issue as interstitial condensation accounted for and interstitial condensation removal process included in build-up
- The thermal performance of the insulation may be reduced when constantly submitted to high RH levels (> 80%)
- The risk of mould growth behind internal wall insulation is probably worsened when there is a '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).

STBA / DECC's guidance

'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.

20.4. Sensitivity Analysis – Change in Material [Cases X.d]: Change in Brick Physical Characteristics

20.4.1. Brick Physical Characteristics

This typology includes a porous material being exposed to wind-driven rain and solar gains (the outer brick layer). The transient modelling of other typologies (e.g. R8 – solid wall with IWI) indicates that the physical characteristics of the brick play a significant role on the hygrothermal performance of the build-up. Therefore, the first sensitivity analysis is carried out with a change in the physical characteristics of the brick, where two additional bricks are tested in addition to the baseline model.

- Baseline Brick: Hand-formed brick (high absorption)

As explained in section 20.2.3, the default brick chosen for the baseline model is considered to be a conservative choice, due to the poor performance of the brick (porosity, water absorption coefficient). This brick can be described as a 'high-absorption' brick. This conservative approach is taken because of a lack of available data for UK building materials.

To assess the impact of brick characteristics onto the hygrothermal performance of this typology, two additional bricks (considered lower absorption) were chosen as alternatives for the first sensitivity analysis. Below is a short summary of their characteristics:

- Sensitivity 1: Solid Brick Masonry

The first lower absorption brick is chosen with a similar density and porosity to the default brick, while having a lower water absorption coefficient (0.110 $kg/m^2\sqrt{s}$ instead of 0.300$kg/m^2\sqrt{s}$).

- Sensitivity 2: Aerated Clay Brick (650 kg/m^3)

The second lower absorbent brick was chosen with much lower density (linked to a higher porosity) compared to the two previous bricks, and has a mid-range A-value of 0.097 $kg/m^2\sqrt{s}$.

20.4.2. Sensitivity Analysis Cases

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the target U-value (as per baseline cases), for each of the two bricks tested in this sensitivity analysis:

Table 48: 4 sensitivity cases (and 4 equilibrium cases)

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	Case 1.d	Case 4.d	Case 7.d	Case 10.d
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
Other	-	-	-	-

20.4.3. Graphs at Critical Junction

The graphs displayed below show the RH levels for each location at the two critical / monitored junctions (similarly to the baseline cases):

- The interface between the inner face of the outer brick layer and the cold side of the cavity wall insulation (listed as monitor 3 here)
- The interface between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation (listed as monitor 11)

The sensitivity analysis cases are displayed as a coloured line (blue for Swansea, purple for Bristol, green for Manchester and orange for London), while their respective baseline cases are displayed with a grey line.

- <u>Sensitivity 1: Solid Brick Masonry</u>

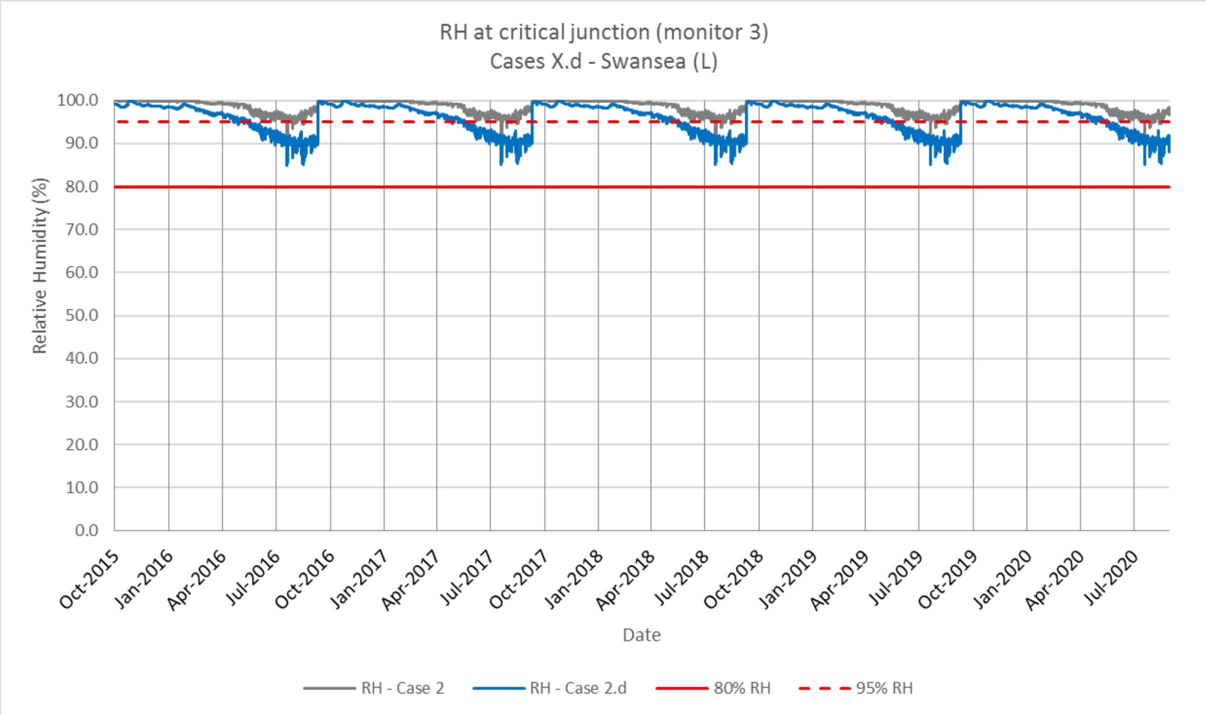


Figure 138: RH levels at critical junction (monitor 3) for Cases 2 and 2.d (masonry brick)

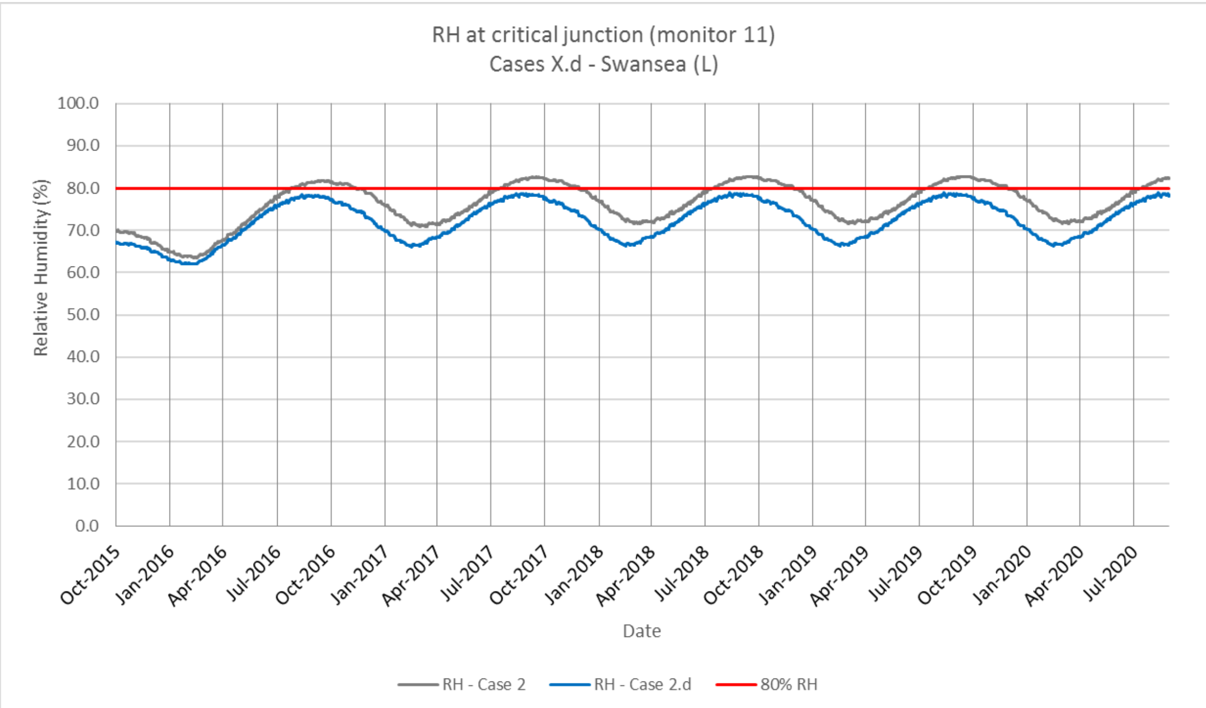


Figure 139: RH levels at critical junction (monitor 11) for Cases 2 and 2.d (masonry brick)

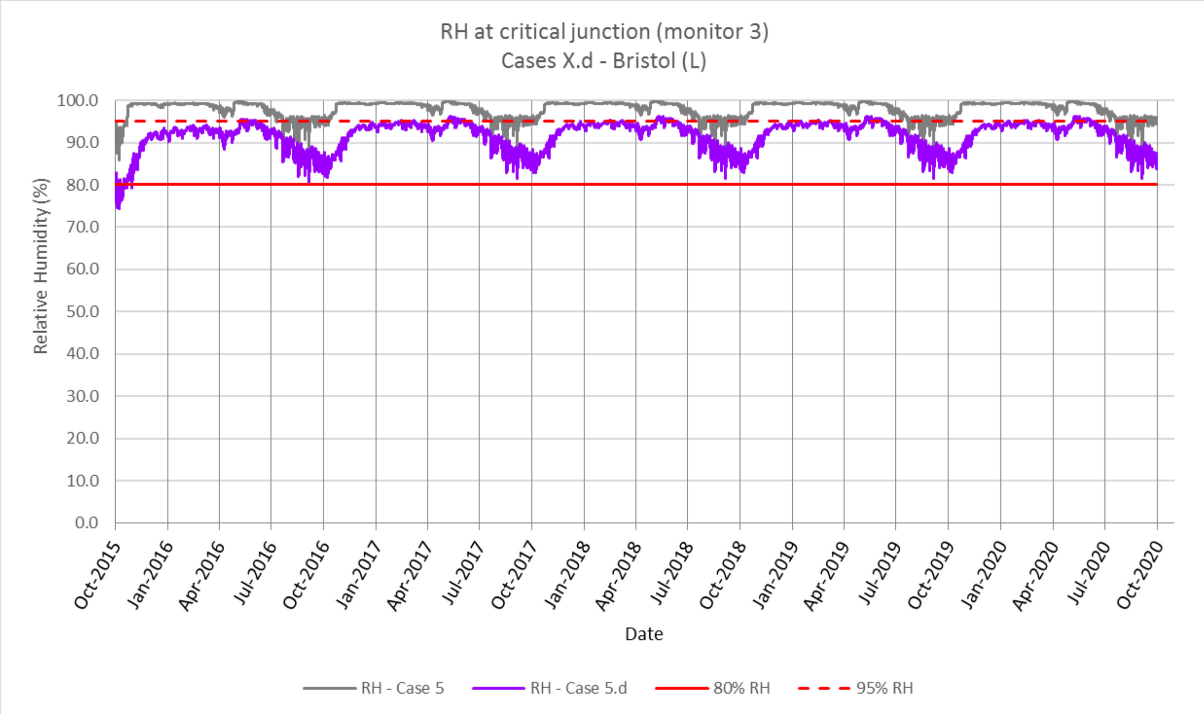


Figure 140: RH levels at critical junction (monitor 3) for Cases 5 and 5.d (masonry brick)

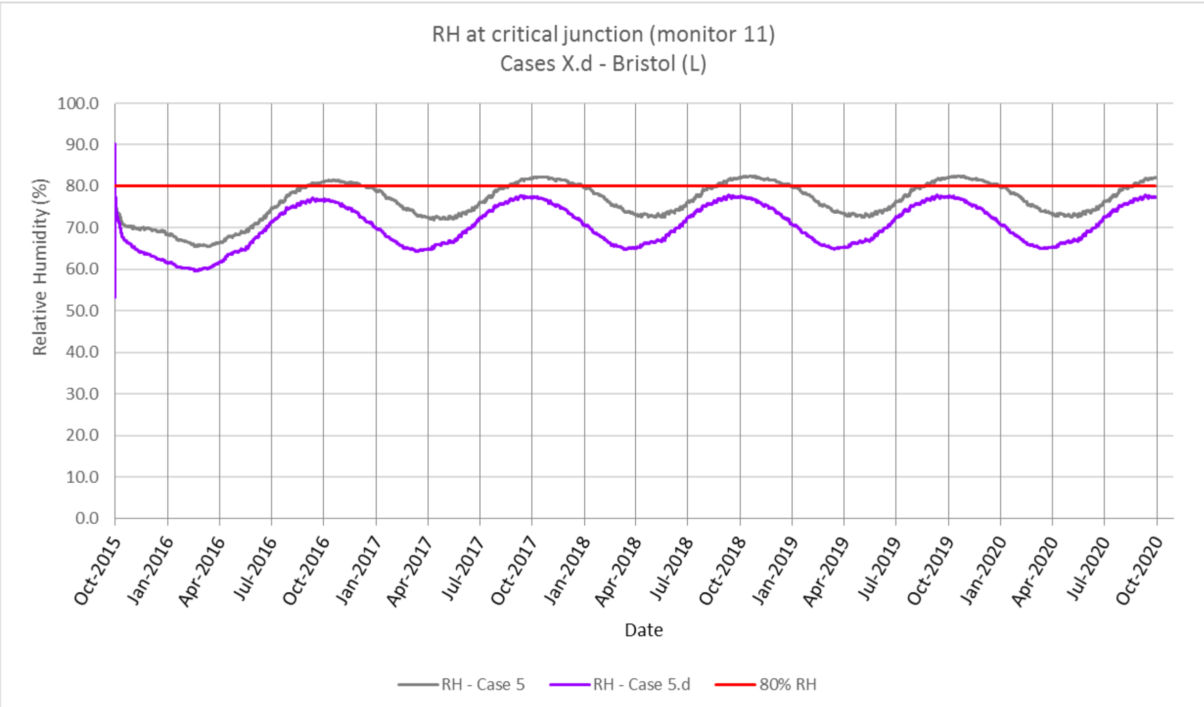


Figure 141: RH levels at critical junction (monitor 11) for Cases 5 and 5.d (masonry brick)

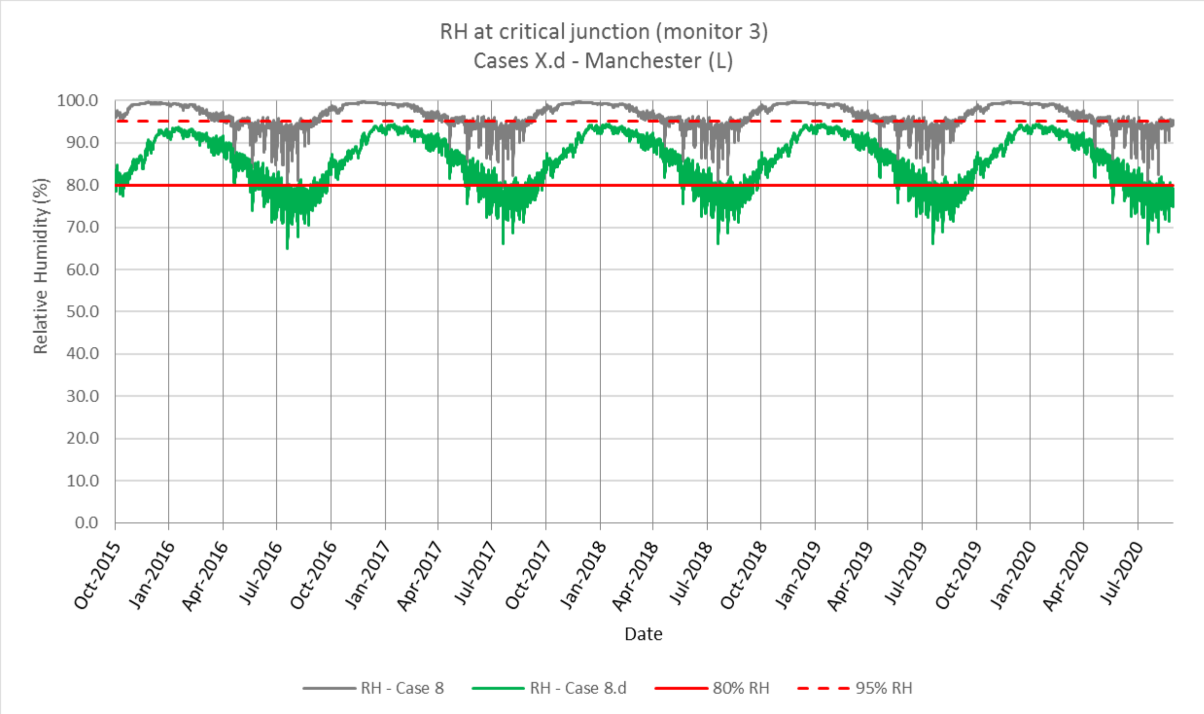


Figure 142: RH levels at critical junction (monitor 3) for Cases 8 and 8.d (masonry brick)

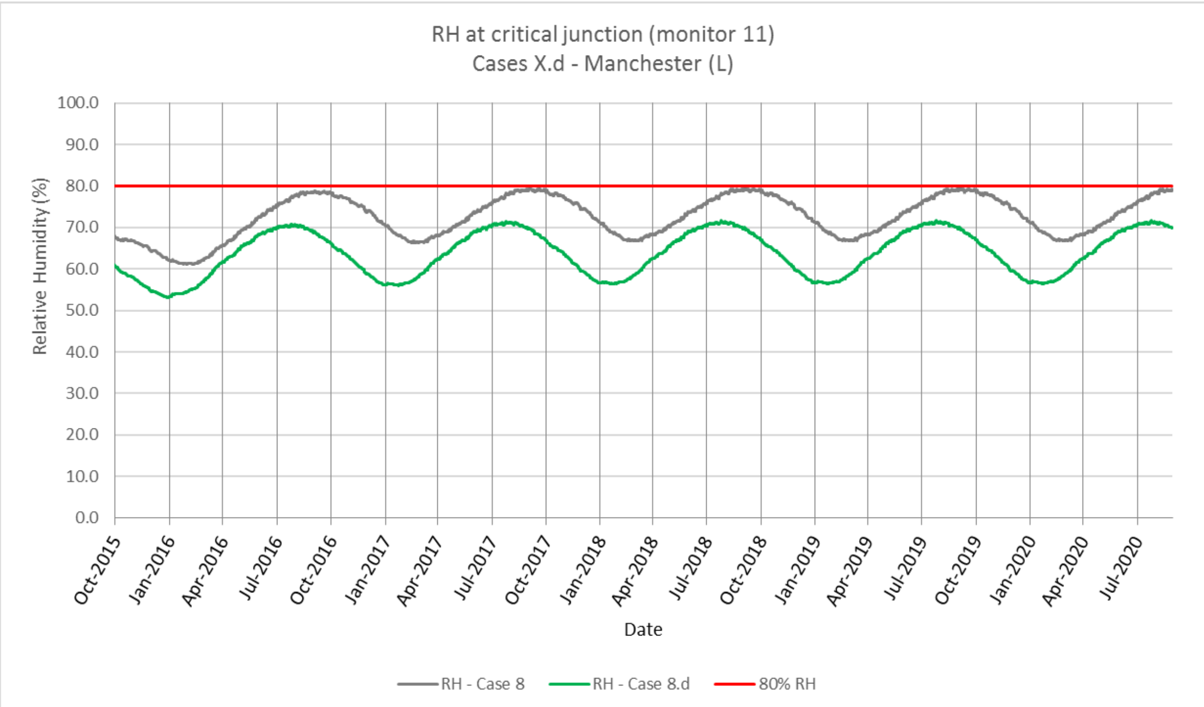


Figure 143: RH levels at monitored junction (monitor 11) for Cases 8 and 8.d (masonry brick)

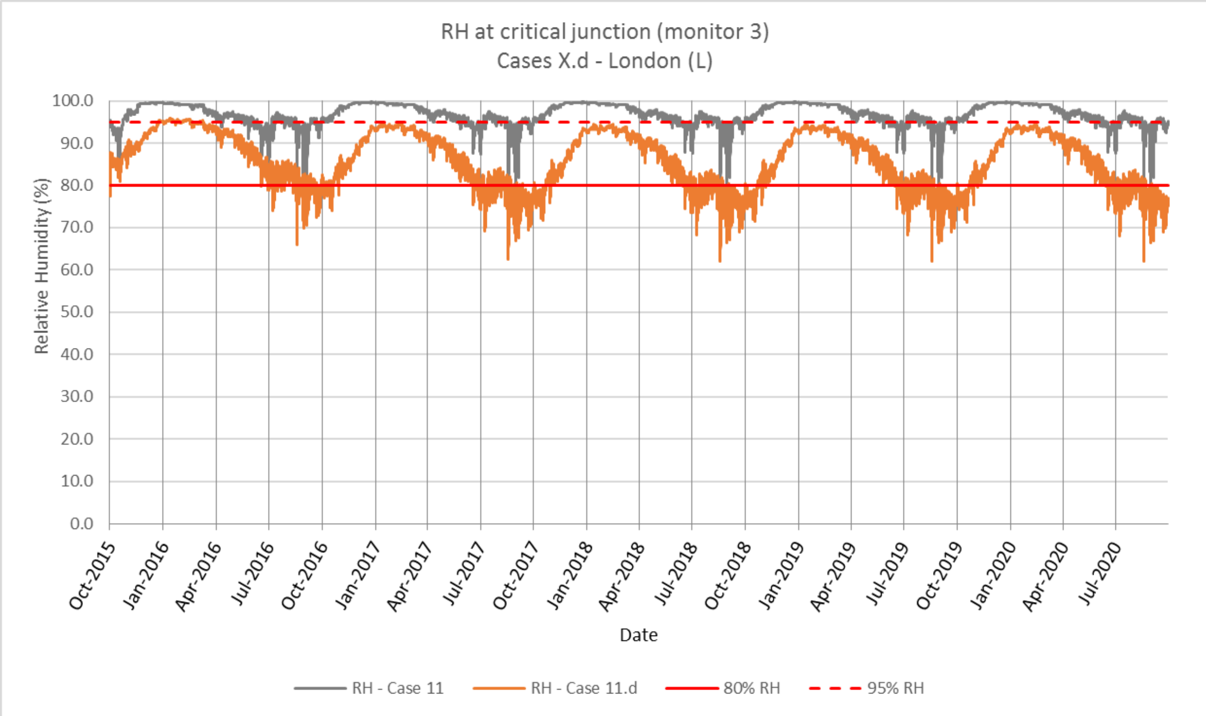


Figure 144: RH levels at critical junction (monitor 3) for Cases 11 and 11.d (masonry brick)

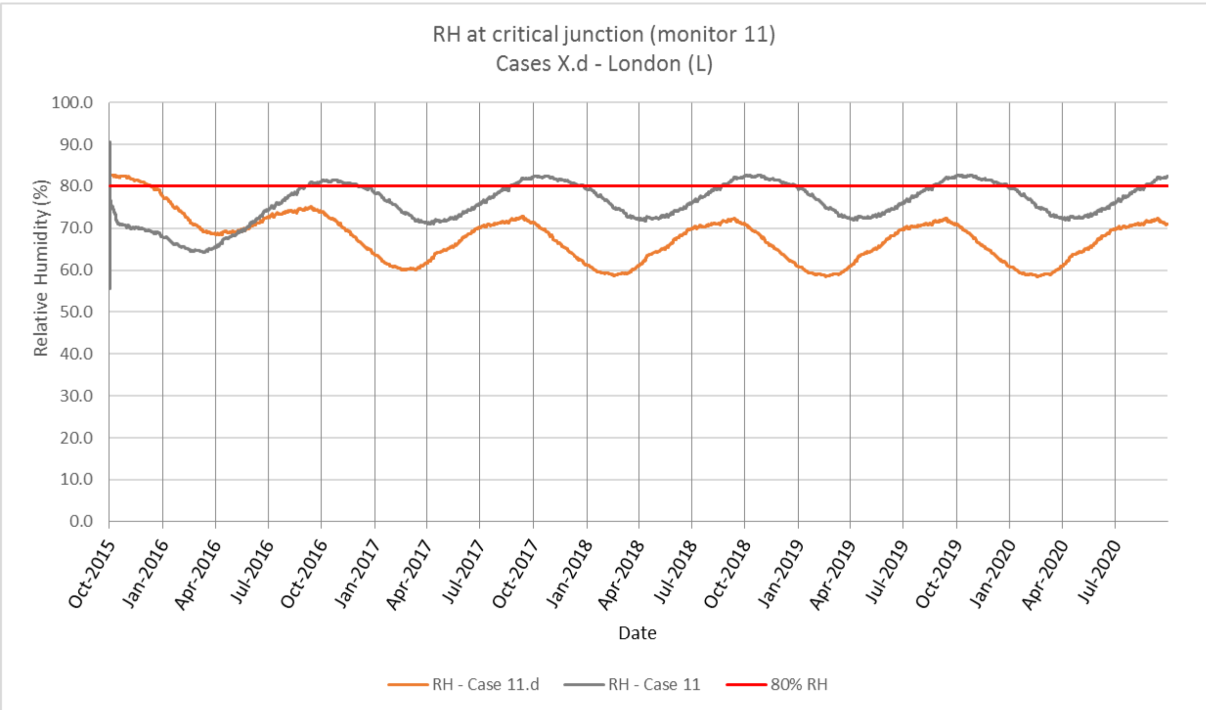


Figure 145: RH levels at monitored junction (monitor 11) for Cases 11 and 11.d (masonry brick)

- <u>Sensitivity 2: Aerated Clay Brick (650 kg/m^3)</u>

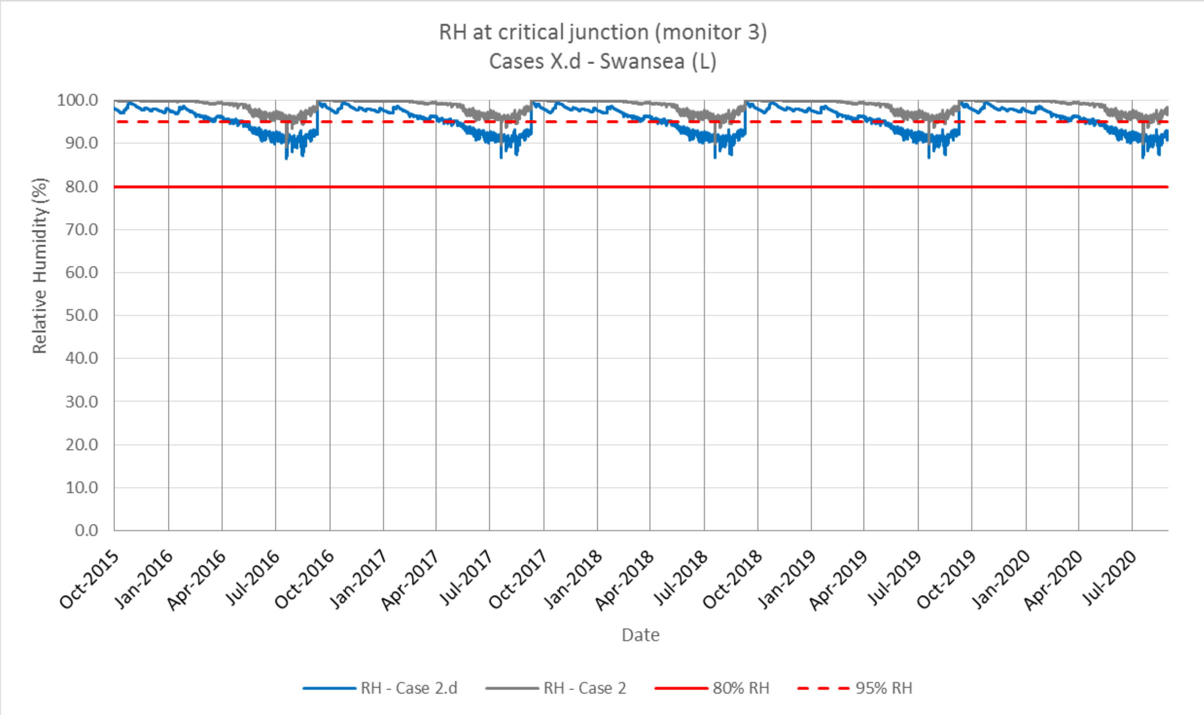


Figure 146: RH levels at critical junction (monitor 3) for Cases 2 and 2.d (clay brick)

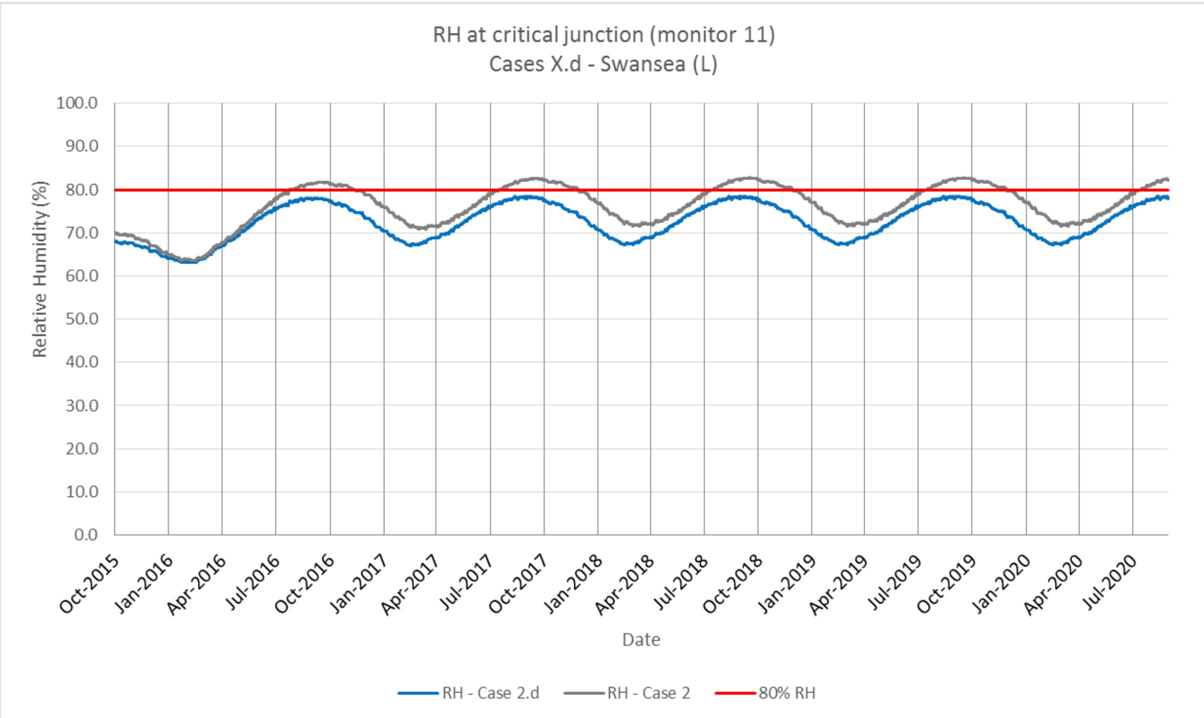


Figure 147: RH levels at critical junction (monitor 11) for Cases 2 and 2.d (clay brick)

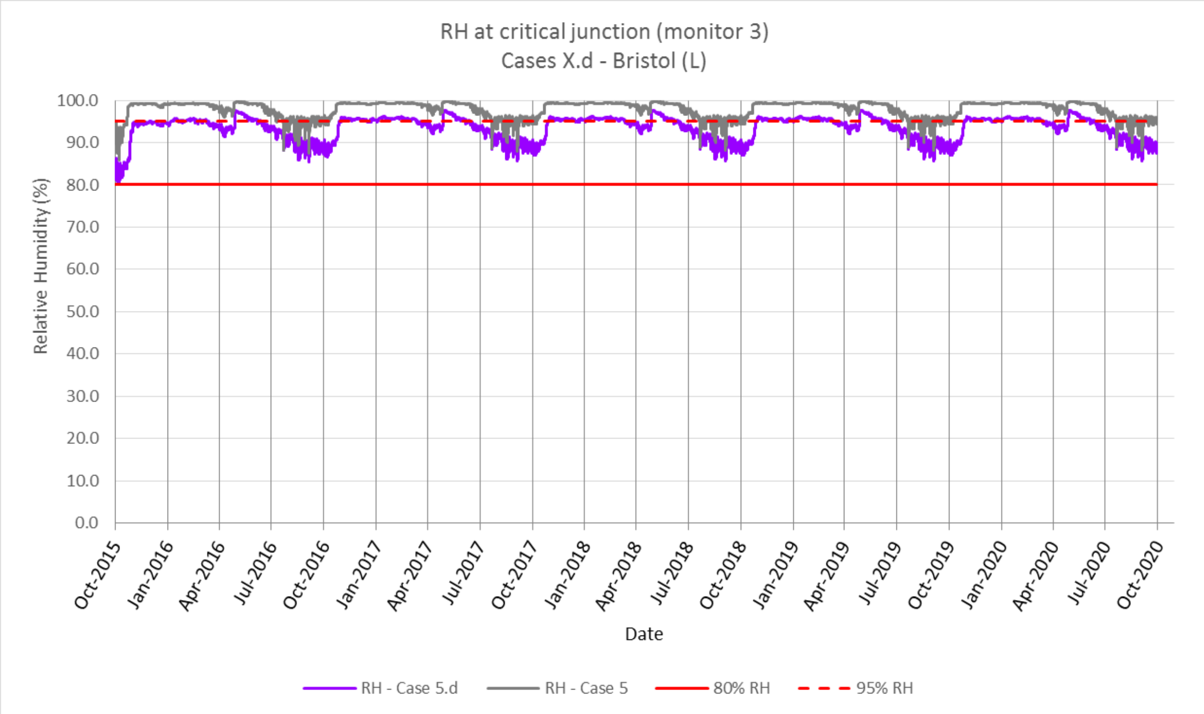


Figure 148: RH levels at critical junction (monitor 3) for Cases 5 and 5.d (clay brick)

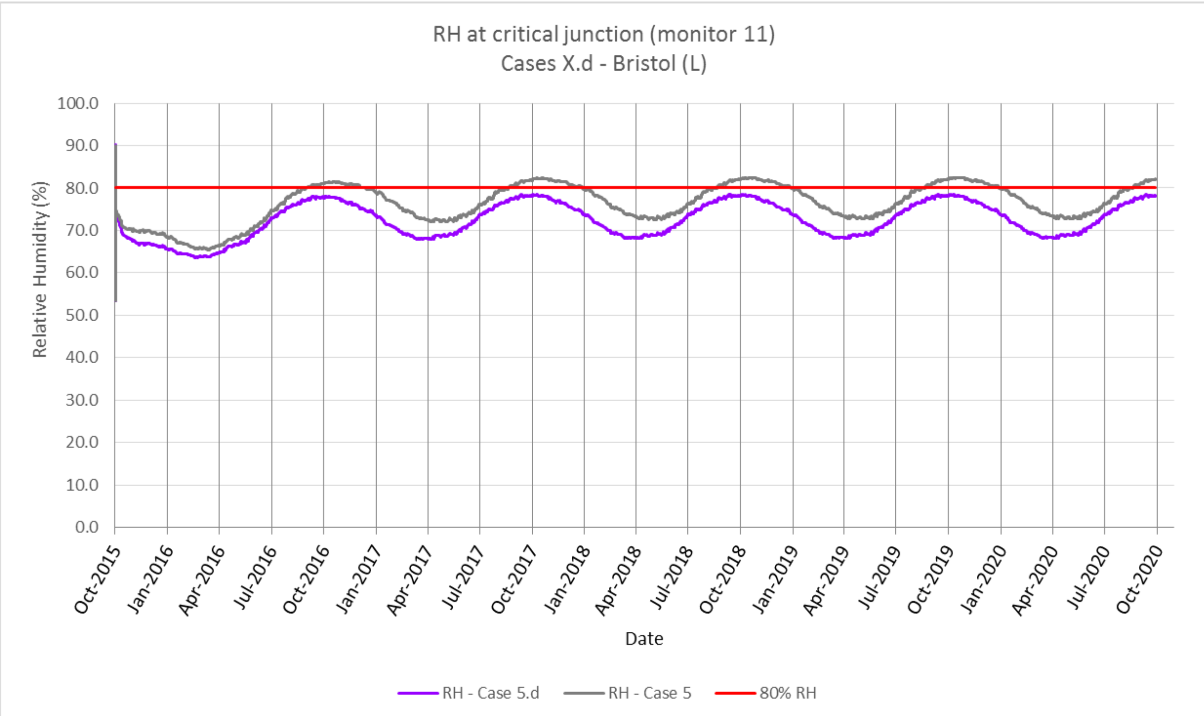


Figure 149: RH levels at critical junction (monitor 11) for Cases 5 and 5.d (clay brick)

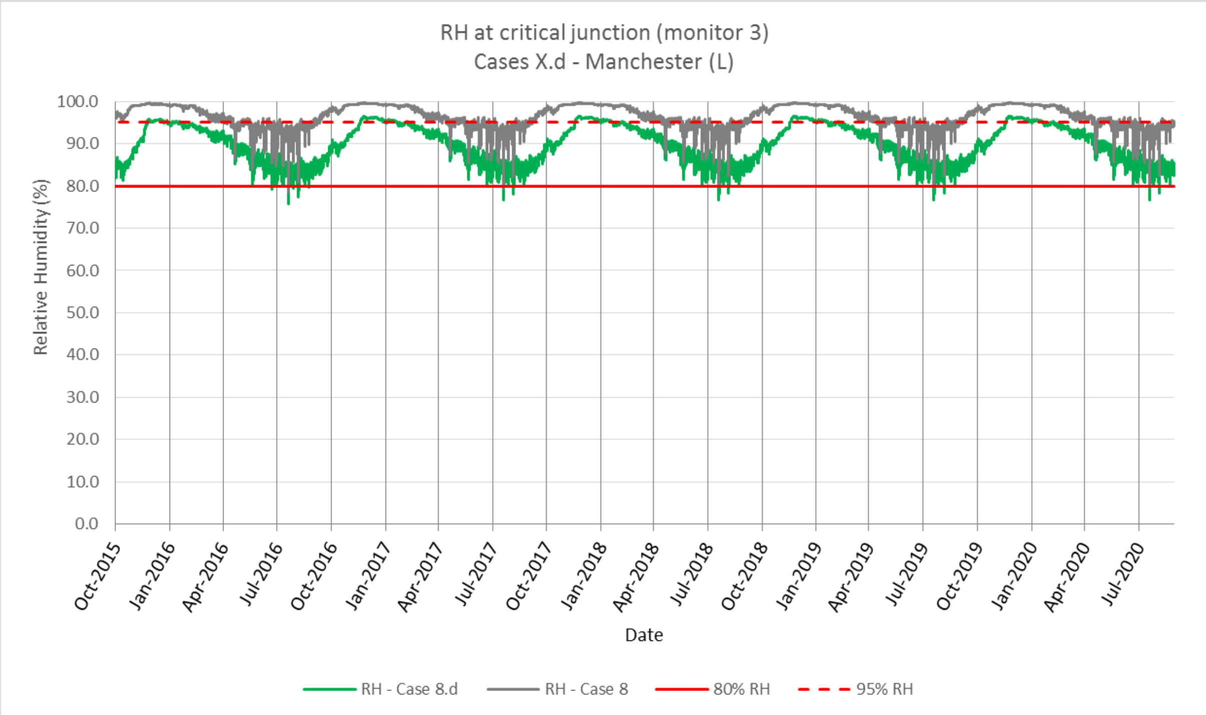


Figure 150: RH levels at critical junction (monitor 3) for Cases 8 and 8.d (clay brick)

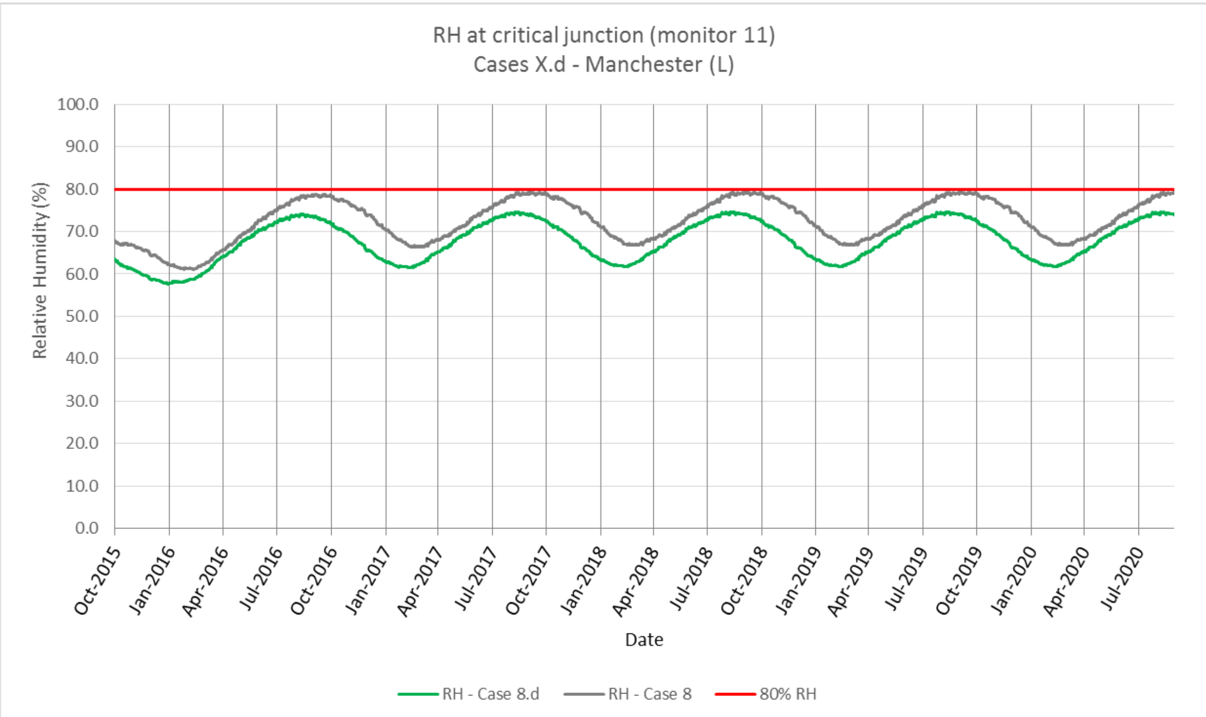


Figure 151: RH levels at monitored junction (monitor 11) for Cases 8 and 8.d (clay brick)

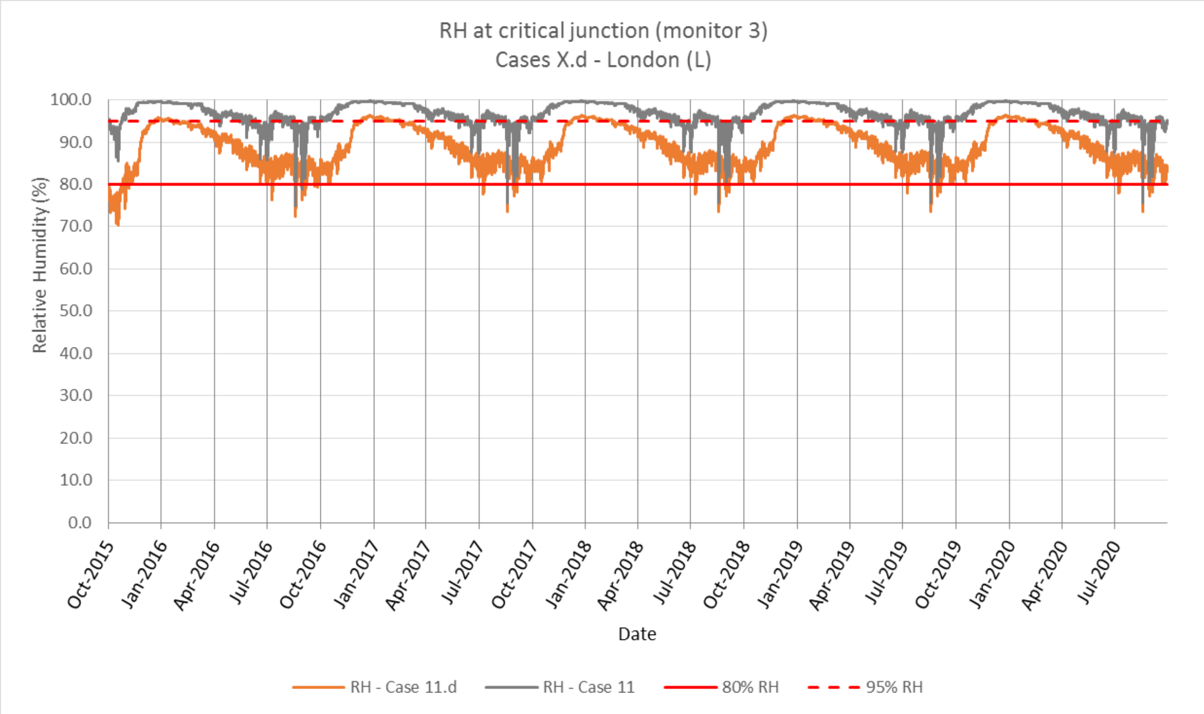


Figure 152: RH levels at critical junction (monitor 3) for Cases 11 and 11.d (clay brick)

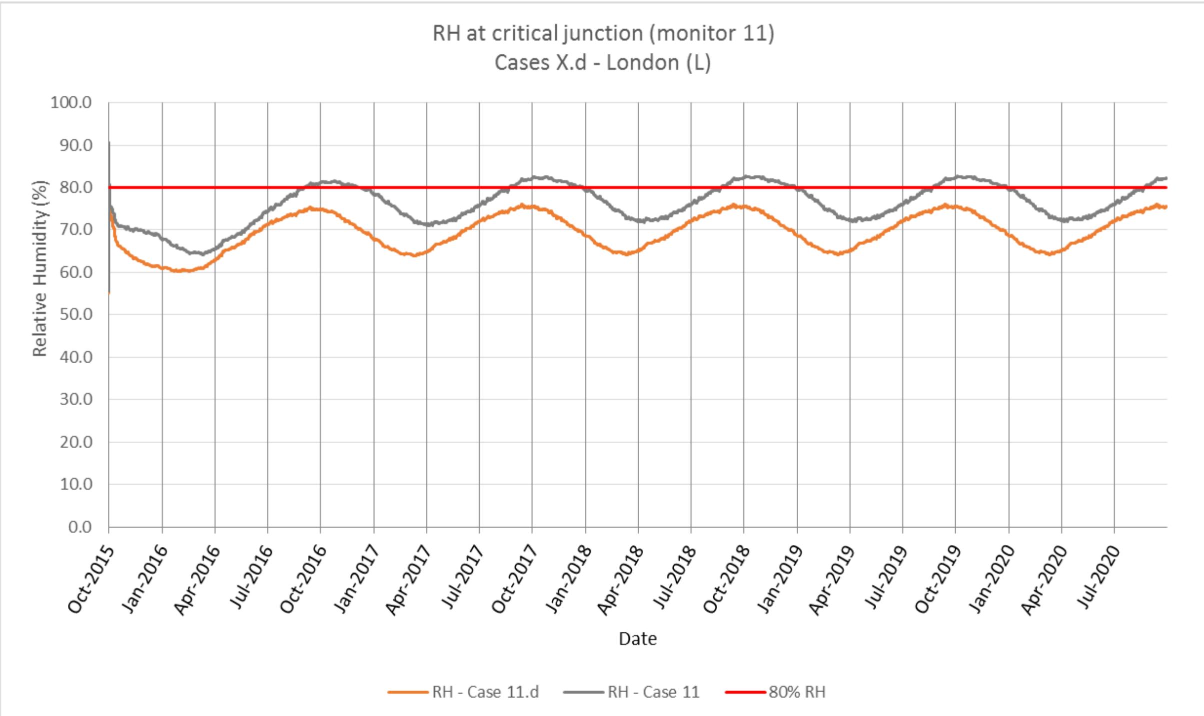


Figure 153: RH levels at monitored junction (monitor 11) for Cases 11 and 11.d (clay brick)

20.4.4. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The graphs show that all cases modelled in this sensitivity analysis perform better than their respective baseline cases, as the RH profiles in the sensitivity analysis are consistently lower than their respective baseline. This improvement in hygrothermal performance brings RH levels at the critical junction between the plastered inner blockwork wall leaf and the retrofitted internal wall insulation permanently below the 80% RH threshold. This means that all cases are considered as ‘pass’ in accordance with the moisture risk assessment criteria listed in section 2.3.

RH levels at the other junction (interface between the inner face of the outer brick layer and the cold side of the cavity wall insulation) are also significantly reduced, staying below the 95% RH threshold for most of the year. The Zone 4 case (Swansea) is the only exception, where RH levels at this junction are kept above 95% for most of the year, with intermittent risk of interstitial condensation (RH at 100%) and still a significant risk of mould growth (as mentioned in the baseline results analysis). This means that this case is listed as ‘risky’ for the above reasons.

Results

The table below summarises the performance of both sensitivity analysis cases:

Table 49: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2.d Risky	Case 5.d Pass	Case 8.d Pass	Case 11.d Pass
Other	-	-	-	-

Effects of brick characteristics

As shown in N12 in the *Using numerical simulation to assess moisture risk in new constructions* report, the water absorption coefficient, called ‘A-value’ is one of the key characteristics of the brick, having a direct and key impact on the hygrothermal performance of the build-up: the lower the A-value of the brick, the more resistant to moisture the build-up is.

These graphs show that, on average, the change in brick characteristics has a significant beneficial impact on the hygrothermal performance of the build-up. The main variable is the brick water absorption coefficient ‘A-value’, with a lower A-value having a direct beneficial impact on the build-up’s performance.
It is worth noting that a lower porosity (normally linked to a higher density) can also improve the hygrothermal performance, as a lower porosity reduces the amount of water uptake from wind-driven rain into the build-up. However, a lower porosity is not an absolute necessity, as shown by the second brick tested in the sensitivity analysis which has a porosity value almost double of the baseline brick.

This improvement in brick characteristics is mostly significant enough to improve the hygrothermal performance of the build-up and change the cases' status from 'fail' to 'pass' (except for the exception of the case in Zone 4, considered 'risky'). These results show that this build-up could be considered a 'safe' build-up under these conditions.

<u>Wall Cavity Depth</u>

It is important to note that the modelling results are only valid the specified build-up, which specifically includes a 75mm full-fill cavity.

If a similar build-up includes a 50mm cavity (instead of a 75mm cavity), these results cannot be used. Indeed, the thickness of the IWI layer will need to be increased to retain the same Part L target U-value if the cavity is reduced from 75 to 50mm. This change would be detrimental for the hygrothermal performance of the build-up, as the critical junction would be kept at a lower temperature and therefore, the RH levels at this junction would increase.

However, from experience, it is highly unlikely that 50mm cavity wall would be insulated with full-fill mineral wool at construction or retrofitted with blown cavity wall insulation, in addition to the installation of the IWI retrofit measure. As this precise build-up is viewed as a very uncommon occurrence, no further analysis was performed.

20.5. Sensitivity Analysis – Change in Orientation [Cases X.c]: North-facing walls

As the build-up is exposed to the wind-driven rain, which has a significant impact on its hygrothermal performance, the second sensitivity analysis would be to change the orientation of the façade. With this sensitivity analysis, the orientation is changed from South-West to North. As explained in typology R8 (solid wall with IWI), the build-up on a South-West facing orientation experiences more wind-driven rain but benefits from greater solar gains (allowing it to dry out quicker). In comparison, a build-up on a North facing orientation experiences less wind-driven rain, which is beneficial to its hygrothermal performance. However, the lack of solar gains leads to a reduction in drying capabilities, which is detrimental to its hygrothermal performance.

We have not run the models, as this analysis was already performed on the N12 (fully filled cavity wall). The results showed that (on average), the sensitivity analysis cases perform similarly or slightly better than their respective baseline cases. However, this improvement in hygrothermal performance from the baseline results, which is present only in some cases, is minimal and does not bring RH levels at the critical junction below the 80% RH threshold for most of the year. This means that all cases retain the same status as those in the baseline assessment and would 'fail' the moisture risk assessment criteria.

21. Typology R14.1: Framed building (timber framed) Retrofit Measure: External Wall Insulation (EWI)

The R14.1 typology is a timber frame wall with a non-porous finish (e.g. render). The retrofit measure is the use of EWI (external wall insulation) on the external side of the timber frame.

The R14.1 typology was originally modelled as a timber frame build-up with no ventilated air gap behind the external finishing layer. However, the vast majority of timber frame systems are built with a ventilated cladding (such as timber cladding or brick skin). Therefore, the build-up of this typology has been changed from the *Using calculation methods to assess surface and interstitial condensation* report, to reflect typical build-ups currently used in the industry.

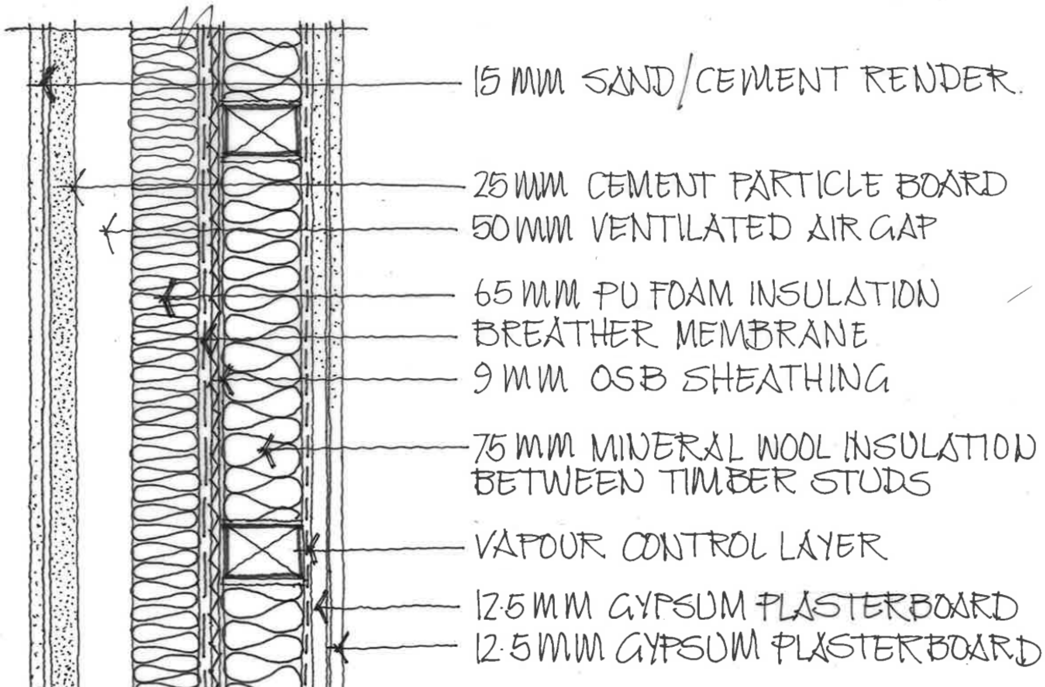


Figure 154: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

21.1. Build-up

21.1.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 15mm sand and cement render *(considered outside of the WUFI build-up)*
- 25mm cement particle board *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 1mm breather membrane (sd = 0.04m)
- 9mm OSB
- 75mm mineral wool insulation (λ = 0.040 W/m.K) between timber studs
- 1mm AVCL layer (sd = 2m)
- 12.5mm gypsum plasterboard
- 12.5mm gypsum plasterboard

21.1.2. WUFI Build-up (post-retrofit)

As the vast majority of timber frame systems are built with a ventilated cladding and it is assumed in this case that the same external finish is to be used on the build-up prior and after retrofit, the following assumption is made: the existing cladding prior-retrofit is removed from the build-up, to allow for the retrofitted insulation layer to be installed externally straight onto the frame. The ventilated air gap to protect the cladding is then re-installed on the outside of the build-up.

Build-Up:

- 15mm sand and cement render *(considered outside of the WUFI build-up)*
- 25mm cement particle board *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 65mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm breather membrane (sd = 0.04m)
- 9mm OSB
- 75mm mineral wool insulation (λ = 0.040 W/m.K) between timber studs
- 1mm AVCL layer (sd = 2m)
- 12.5mm gypsum plasterboard
- 12.5mm gypsum plasterboard

It has been assumed that the breather membrane is kept in its original position after the retrofit measure is installed.

The WUFI build-up of R14.1 is identical to Part L case in N14 of *Using numerical simulation to assess moisture risk in new constructions* report (Timber frame wall – with air gap and a non-porous finish (e.g. render)), with a slight variation in the thickness of the insulation layers. As this modelling work is assessing qualitatively the impact of different measures on the hygrothermal performance of each typology, this slight difference in insulation thicknesses does not have any consequential effect on the results.

The only other difference between the two typologies is the timing of the installation of the external insulation layer. For N14, the external wall insulation is installed simultaneously to the rest of the wall construction; whereas for R14.1, the external wall insulation is retrofitted externally to the timber frame.

As part of the WUFI modelling process (in Section 3.4 of this report), a pre-retrofit build-up is supposed to be run to determine equilibrium levels. However, the materials present in the pre-retrofit build-up are not exposed to wind-driven rain (as they are protected by the external cladding) and are not heavy weight materials. Therefore, it is not 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.

As no equilibrium model is required for R14.1, the initial conditions in the R14.1 WUFI model are identical to the N14 WUFI model. As a result, both R14.1 and N14 have the same WUFI input data and therefore share the same results, despite the difference in the timing of the installation of the external insulation layer. For these reasons, no baseline or sensitivity modelling is performed on this typology and please refer to the *Using numerical simulation to assess moisture risk in new constructions* Report for the results and analysis of typology N14 (Section 18).

22. Typology R14.2: Framed building (timber framed) Retrofit Measure: Internal Wall Insulation (IWI)

The R14.2 typology is a timber frame wall with an air gap and a non-porous finish (e.g. render) prior to retrofit. The retrofit measure is to add Internal Wall Insulation (IWI) on the inside of the plaster board covering the timber frame.

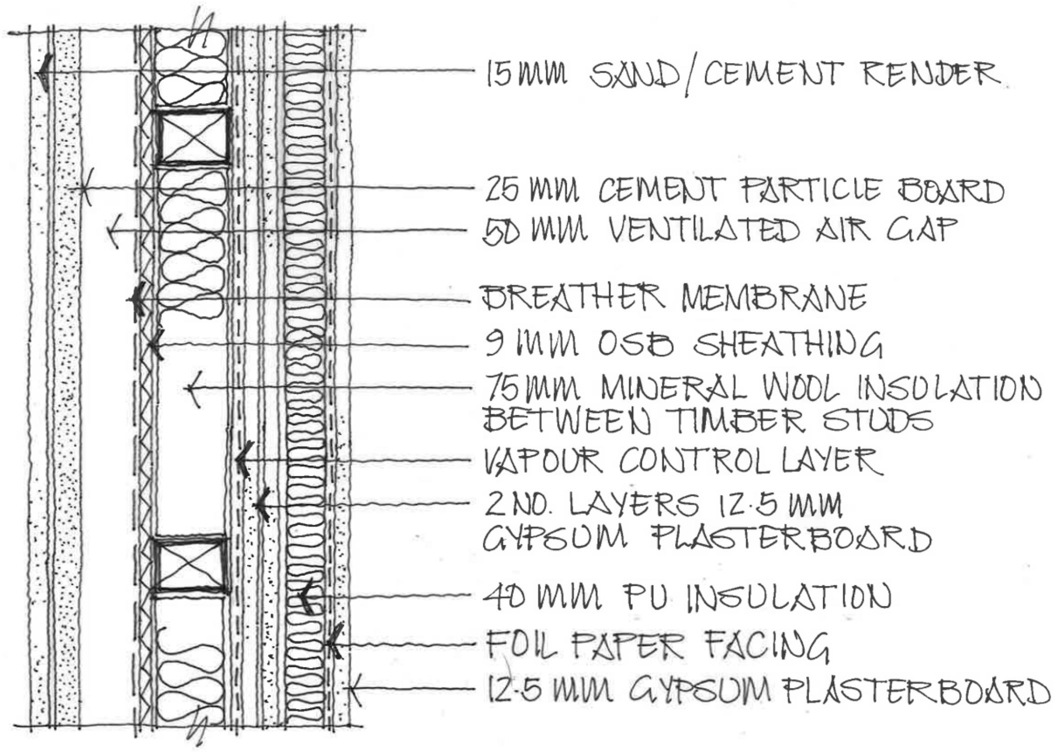


Figure 155: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

22.1. Assessment Method

As BS 5250 (2011) states in the general framed wall section (G.4.1), *'there is a risk of interstitial condensation occurring behind impermeable external finishes or cladding: to avoid that, a vented space should be provided immediately behind the finish or cladding'.*

To follow prescriptive guidance, (similar to N13 build up – New timber frame wall with internal wall insulation), the cavity behind the wall external finish (cement particle board with sand & cement render) is assumed to be ventilated to the outside, to allow any moisture present in the cavity to be removed. This means that the external

finishing layers are considered as a ‘protective cladding’ and are not technically part of the ‘thermal’ build-up. As shown in the following section, the modelled build-up therefore only extends from the breathable membrane (on the cold side of the frame) to the internal finish.
As the outer layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations). Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method.

The results by the Glaser method show that this build-up is considered a ‘safe’ build-up, with no risk of interstitial condensation. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

22.2. Build-up

22.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 15mm sand and cement render *(considered outside of the WUFI build-up)*
- 25mm cement particle board *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 1mm breather membrane (sd = 0.04m)
- 9mm OSB
- 75mm mineral wool insulation (λ = 0.040 W/m.K) between timber studs
- 1mm AVCL layer (sd = 2m)
- 12.5mm gypsum plasterboard
- 12.5mm gypsum plasterboard

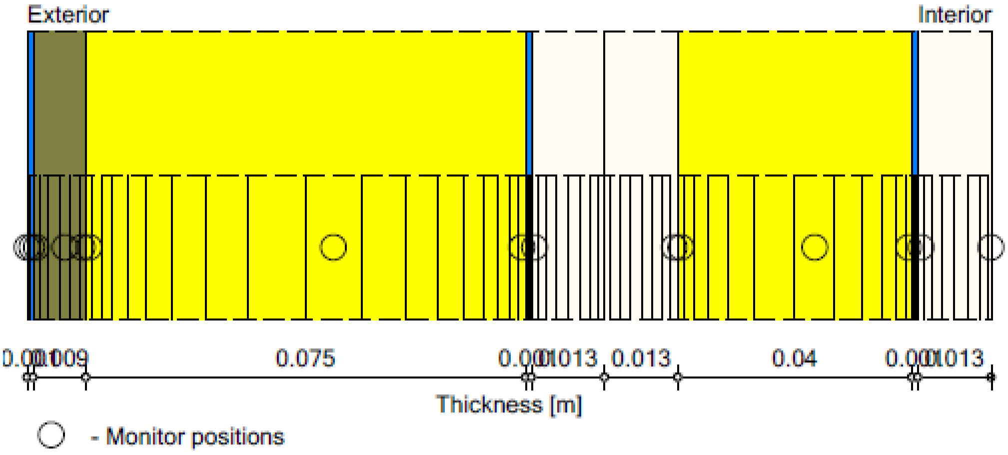
22.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are not exposed to wind-driven rain and are not heavy weight materials. Therefore, it is not 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.

22.2.3. WUFI Build-up (post-retrofit)

Build-Up:

- 15mm sand and cement render *(considered outside of the WUFI build-up)*
- 25mm cement particle board *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 1mm breather membrane (sd = 0.04m)
- 9mm OSB
- 75mm mineral wool insulation (λ = 0.040 W/m.K) between timber studs
- 1mm AVCL layer (sd = 2m)
- 12.5mm gypsum plasterboard
- 12.5mm gypsum plasterboard
- 40mm polyurethane insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 12.5mm gypsum plasterboard



Materials:

- *weather resistive barrier (sd=0,04m) (unlocked) 0.001 m
- Oriented Strand Board (density 615 kg/m³) 0.009 m
- Mineral Wool (heat cond.: 0,04 W/mK) 0.075 m
- vapour retarder (sd=2m) 0.001 m
- Gypsum Board 0.013 m
- Gypsum Board 0.013 m
- *PU (heat cond.: 0,025 W/mK) 0.04 m
- *Foil paper facing (sd = 14m) (unlocked) 0.001 m
- Gypsum Board 0.013 m

WUFI Input Parameters

As the cavity is considered ventilated, the cement particle board, the external render layer and the 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 breather membrane) is exposed to different external conditions due to the external finishing layers 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 cement particle board is protecting the external surface of the timber frame)
- 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

22.3. Baseline Results

22.3.1. Baseline Cases

The 4 baseline cases are set across the four wind-driven rain exposure zones, meeting the Part L target U-value, as set out below.

Table 50: 4 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

22.3.2. Critical and Monitored Junctions

Prescriptive guidance BS 5250 (2011) (paragraph G.4.1.) states that *‘there is a risk of interstitial condensation occurring on the inner surface of any sheathing applied directly to the outside of the framing’.* Therefore, all graphs will display RH levels at the interface between the OSB (sheathing) and the cold side of the insulation layer within the frame (mineral wool).

This critical junction is not identified by the BS EN ISO 13788 (2012), as this calculation shows no presence of interstitial condensation in the build-up throughout the year.

As the additional layer of retrofit insulation has been added internally, the junction of the existing plasterboard finish and the new internal wall insulation is monitored.

22.3.3. Graphs at Critical and Monitored Junctions

The graphs displayed below show the RH levels for each location at the two critical / monitored junctions:

- The interface at the critical junction, between the OSB (sheathing) and the cold side of the mineral wool insulation layer within the frame (monitor 5)
- The interface at the additional monitored junction, between the existing plasterboard and the retrofitted insulation layer (monitor 10)

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).

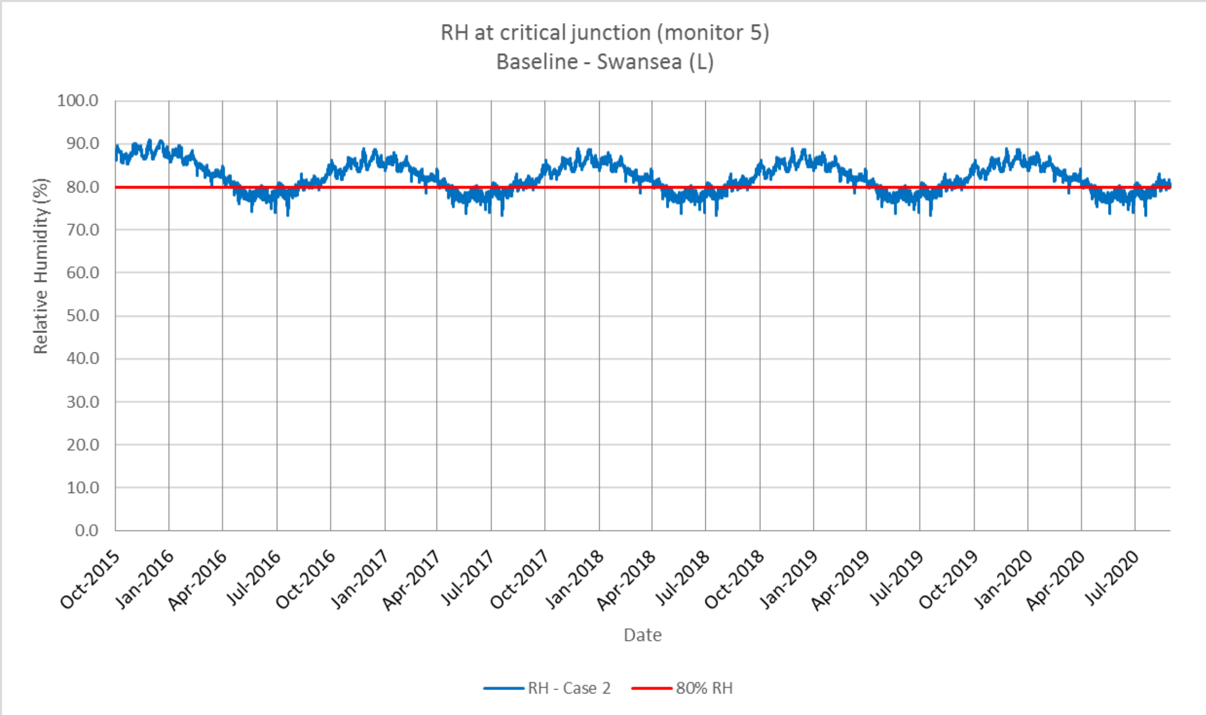


Figure 156: RH levels at critical junction (monitor 5) for Case 2

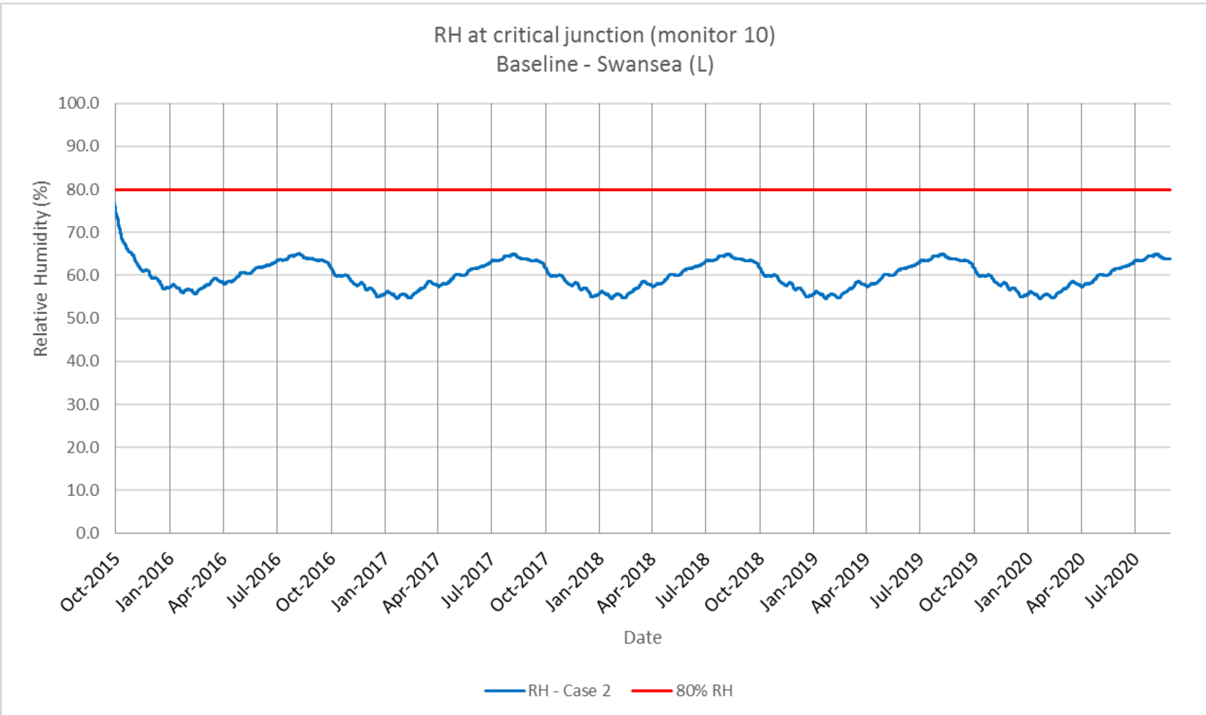


Figure 157: RH levels at additional monitored junction (monitor 10) for Case 2

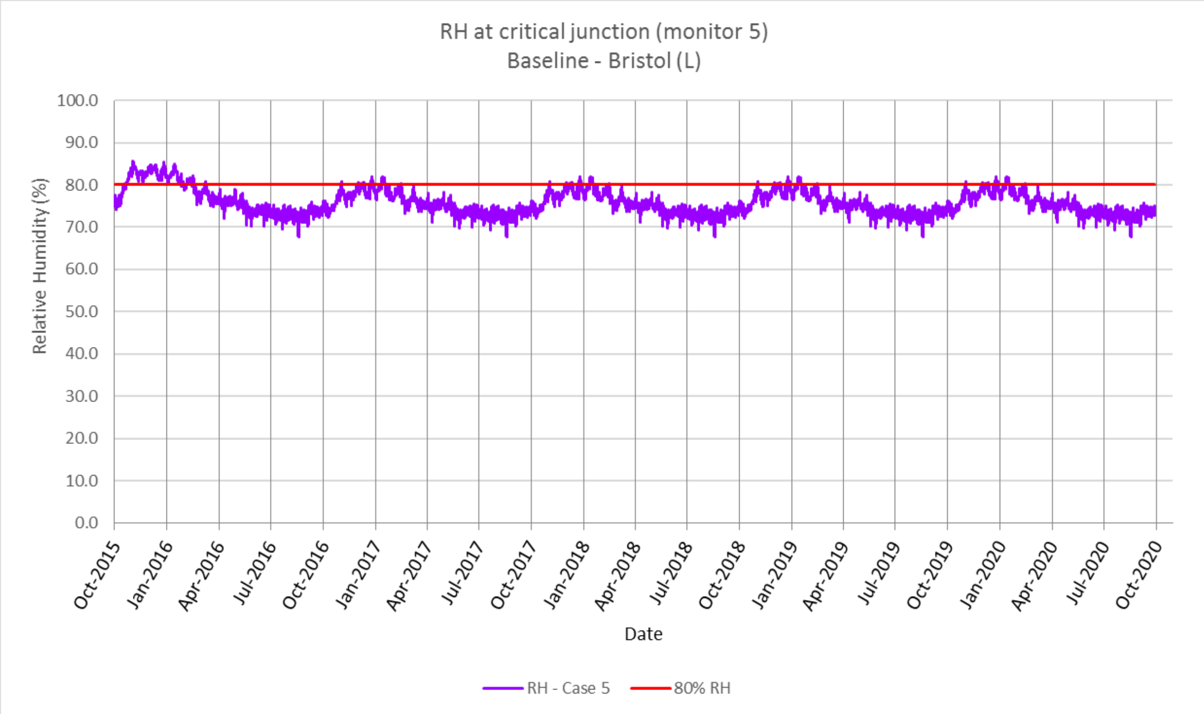


Figure 158: RH levels at critical junction (monitor 5) for Case 5

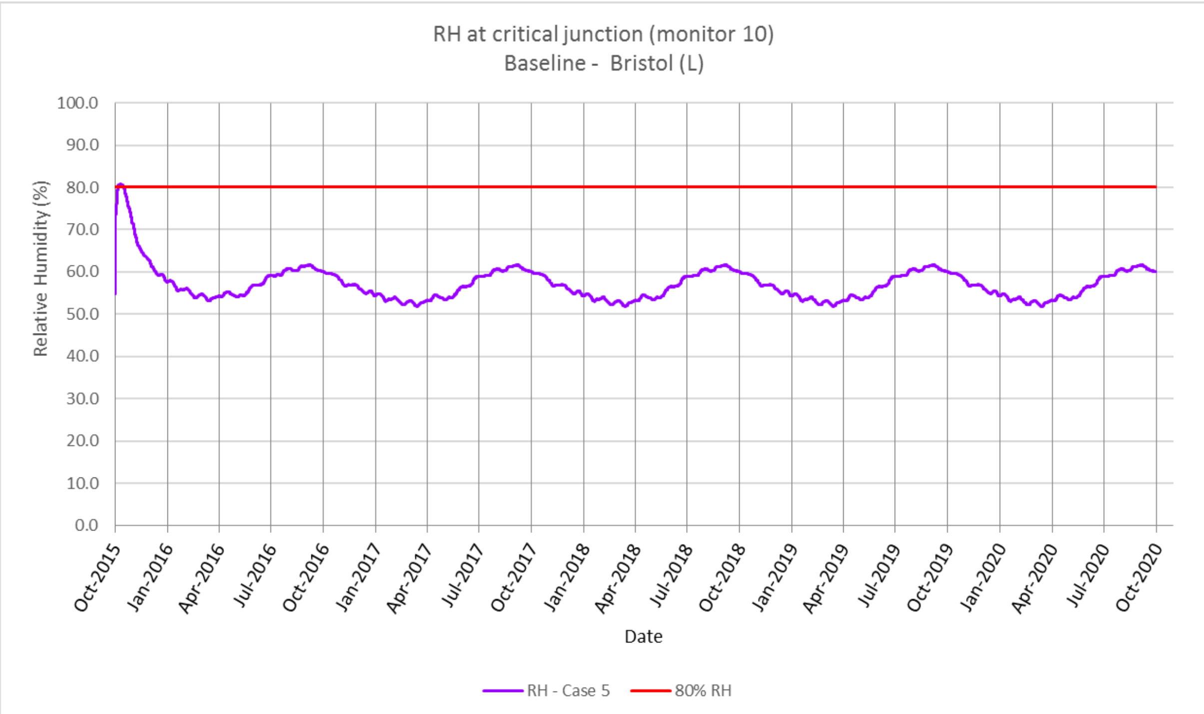


Figure 159: RH levels at additional monitored junction (monitor 10) for Case 5

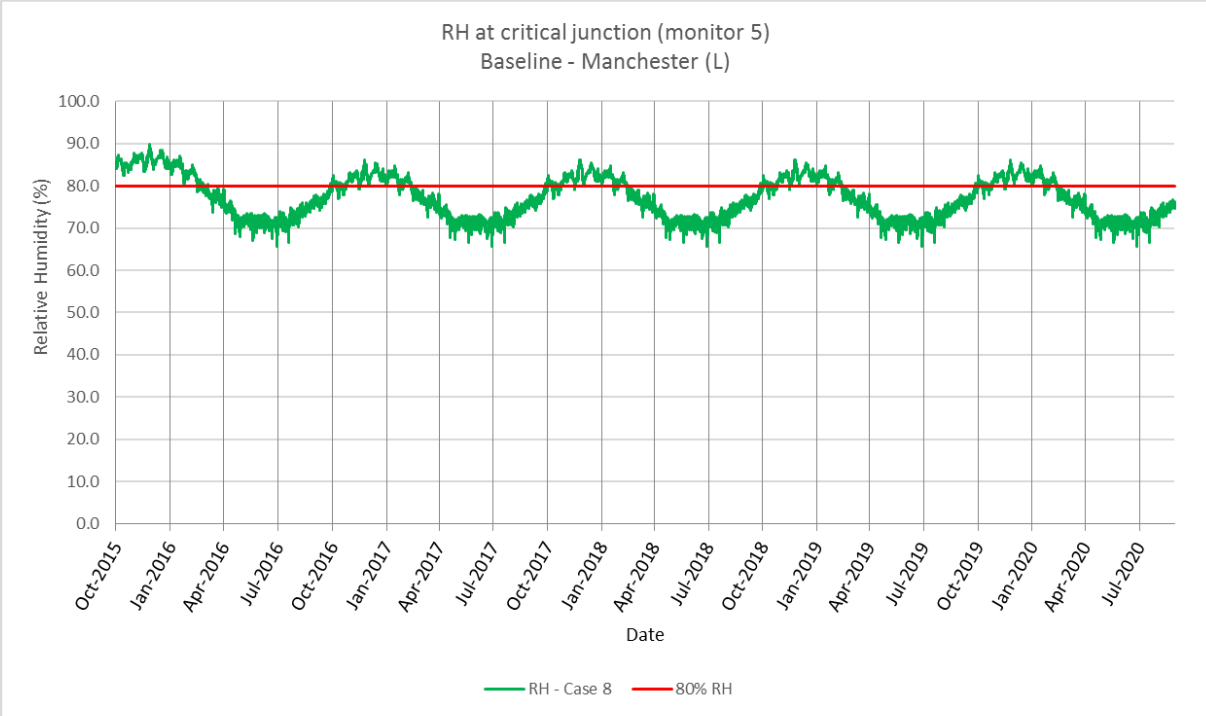


Figure 160: RH levels at critical junction (monitor 5) for Case 8

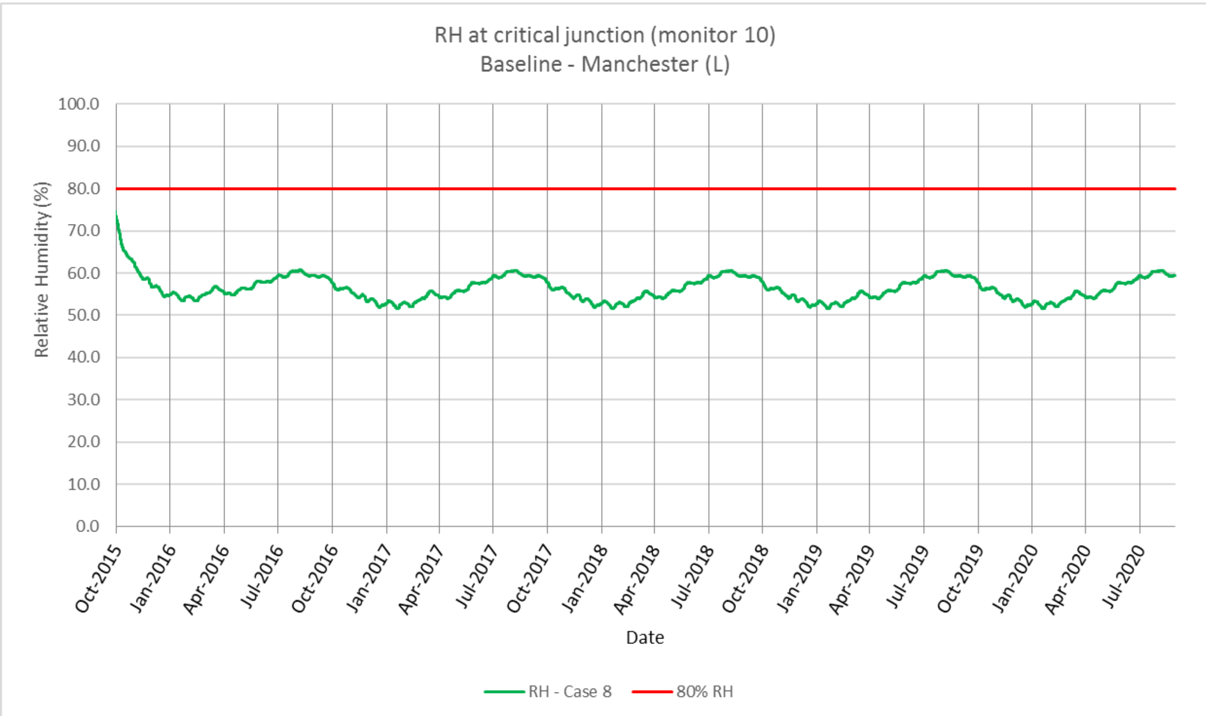


Figure 161: RH levels at additional monitored junction (monitor 10) for Case 8

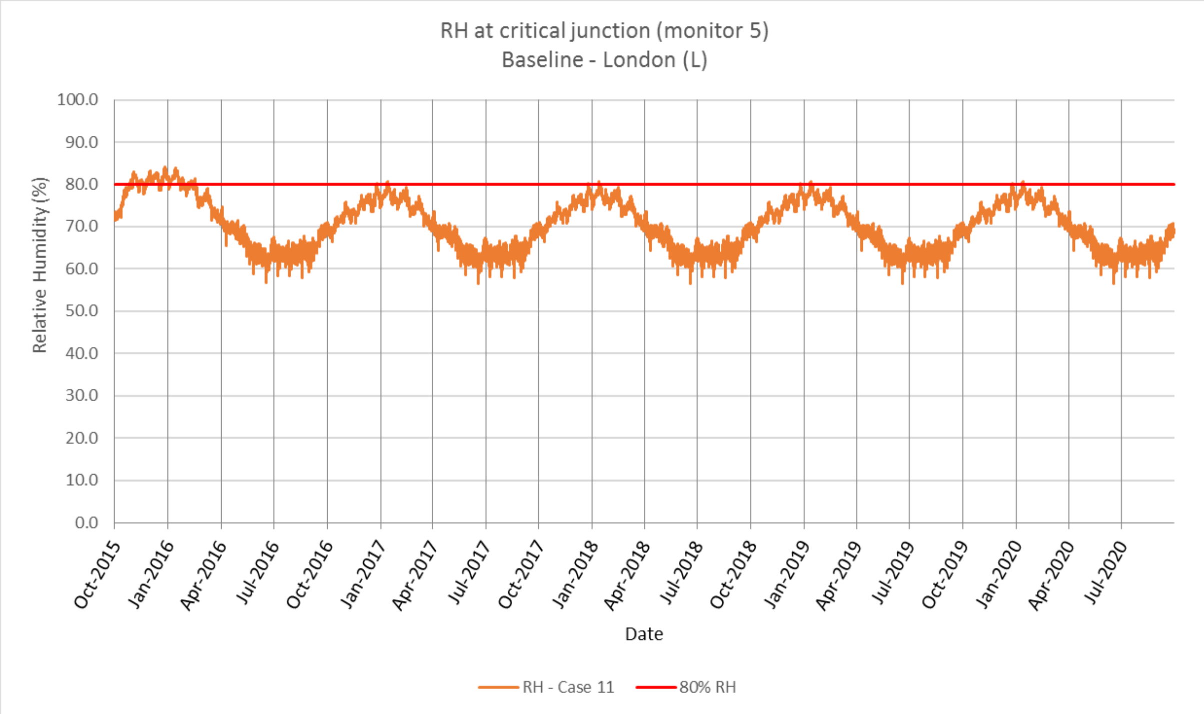


Figure 162: RH levels at critical junction (monitor 5) for Case 11

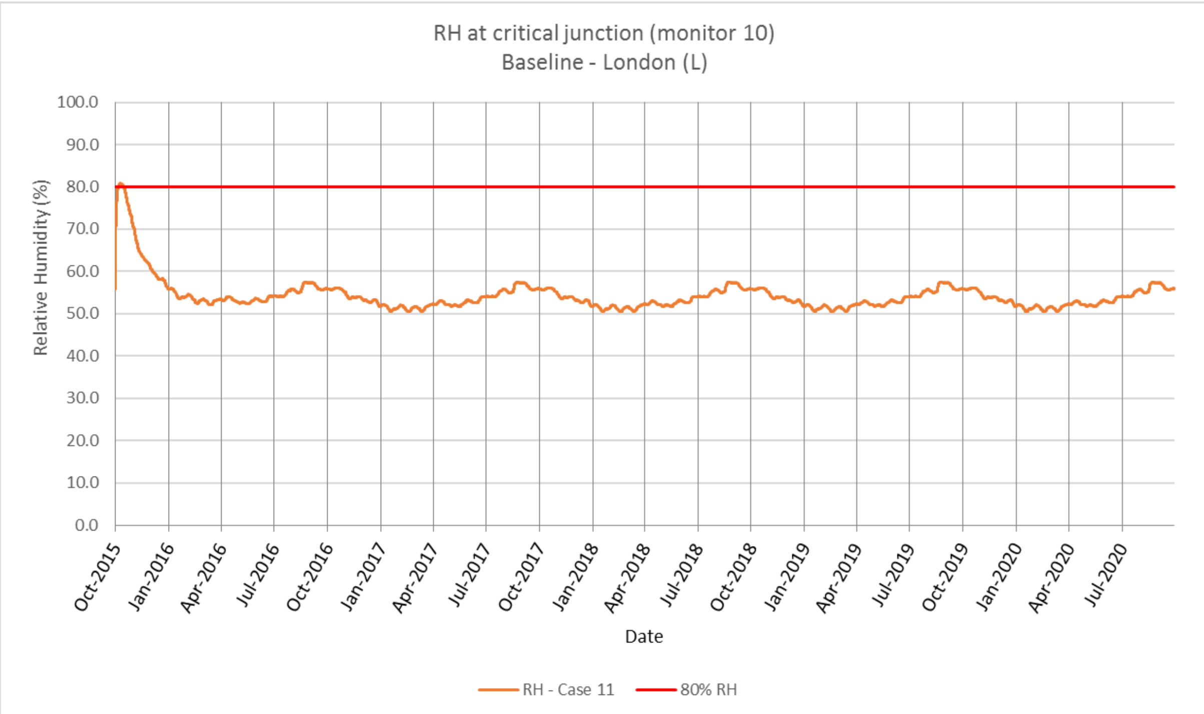


Figure 163: RH levels at additional monitored junction (monitor 10) for Case 11

22.3.4. Results Analysis

Moisture risk assessment criteria

The critical surface RH level of 80% has been maintained in both positions, due to the presence of 'fragile' materials (timber and plasterboard) at each junction.

All cases achieve equilibrium. However, some cases display intermittent RH levels above the 80% RH threshold, sometimes for relatively long periods of time. Where these periods last for longer than a month, these cases are declared as 'fail', as they do not meet the second criteria listed in the assessment risk criteria in section 2.3.

For this reason, the results are as follow:

- Cases in Zone 4 - Swansea and Zone 2 - Manchester are considered 'fail'
- Case in Zone 3 - Bristol is considered 'risky'
- Case in Zone 1 - London is considered 'pass'

However, despite these 'fail' results, the risk of mould growth is not as significant as it could be because RH peaks only happen during the winter period when lower temperatures occur, which does not promote mould growth. In addition, as mineral wool is very flexible, this type of insulation is typically tightly fitted between the timber studs and does not tend to leave air gaps around the OSB layer when correctly installed.

In all cases, the additional monitored inner junction shows safe RH levels well below 80%.

Results

These results are summarised in the table below.

Table 51: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Fail	Case 5 Risky	Case 8 Fail	Case 11 Pass
Other	-	-	-	-

None of the cases display risks of interstitial condensation, as in all cases, the RH levels do not reach 100% at any point during the year. This is in line with the BS EN ISO 13788 (2012) calculations.

Effects of exposure zones

The effects of exposure zones are only slightly visible on the graphs. As the build-up is sheltered from wind-driven rain and the cases in Zones 4 - Swansea and Zone 2 - Manchester fail while the case in Zone 3 - Bristol is only considered ‘risky’, it seems that the high RH and colder temperatures present as external conditions have a more significant effect on the hygrothermal performance of the build-up, rather than the exposure to wind-driven rain.

22.3.5. Timber Moisture Levels

As one of the materials at the critical junction is timber, which is considered to be a ‘fragile’ material, the water content in this layer is analysed.

Water content in material is normally expressed in kg/m^3 (kg of water per m^3 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 when moisture content in timber starts reaching 18%, the load-bearing capacity of structural wood elements starts to decrease.

The graph below displays the moisture content in M-% in the external chipboard layer for the Case 2.

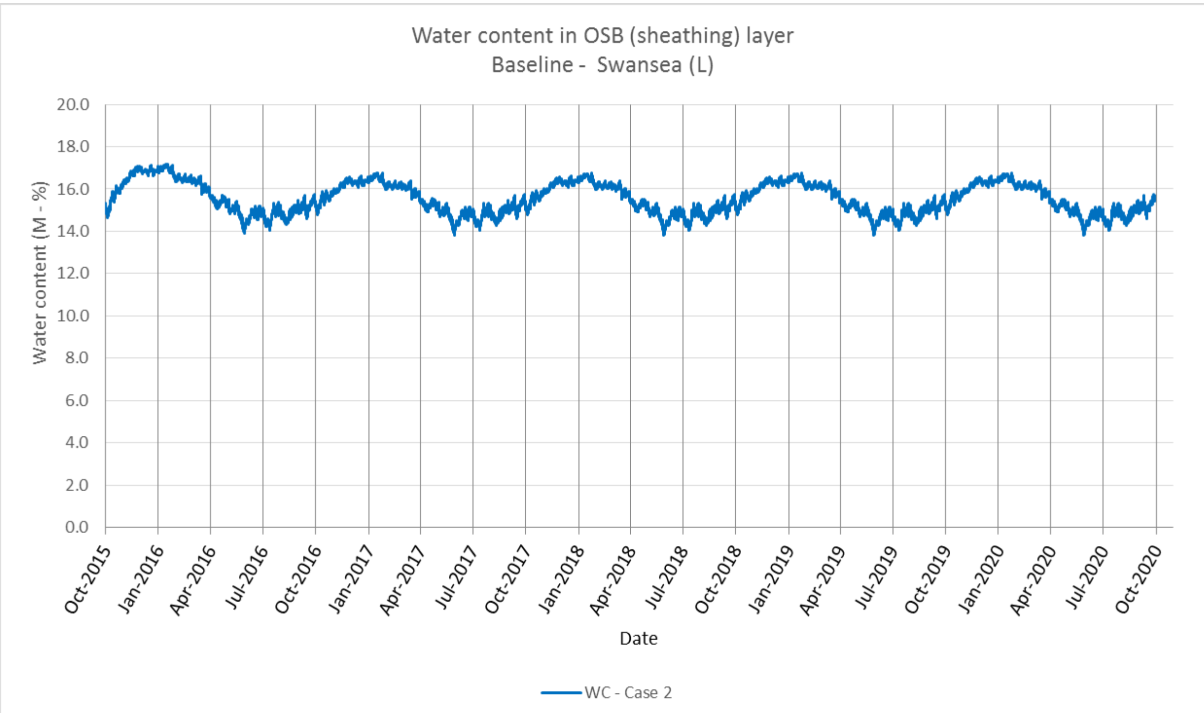


Figure 164: Moisture content in the OSB (sheathing) layer for Case 2

The graph shows that moisture levels in the OSB sheathing layer are considered ‘safe’. These levels show the timber layer is not considered at risk of rotting or structural damage as they are kept below the 18 M-% threshold throughout the year.

It is worth noting that this OSB layer does not play a structural role (only supporting the mineral wool insulation in between timber studs). This means that if this layer was to experience higher moisture content in the timber which could lead to rot or structural damages, this would not have severe consequences on the build-up’s performance.

22.4. Conclusions

- Build-up sheltered from the elements and moisture driven by vapour diffusion, with AVCL on the warm side of the insulation so theoretically safe

23. Typology R17: Cold pitched roof - insulated at ceiling level Retrofit Measure: Additional insulation above timber joists

The R17 typology is a pitched roof that is insulated with 100mm insulation between timber joists prior to retrofit. The retrofit measure is to install an additional continuous insulation layer above the timber joists at ceiling level, i.e. loft insulation.

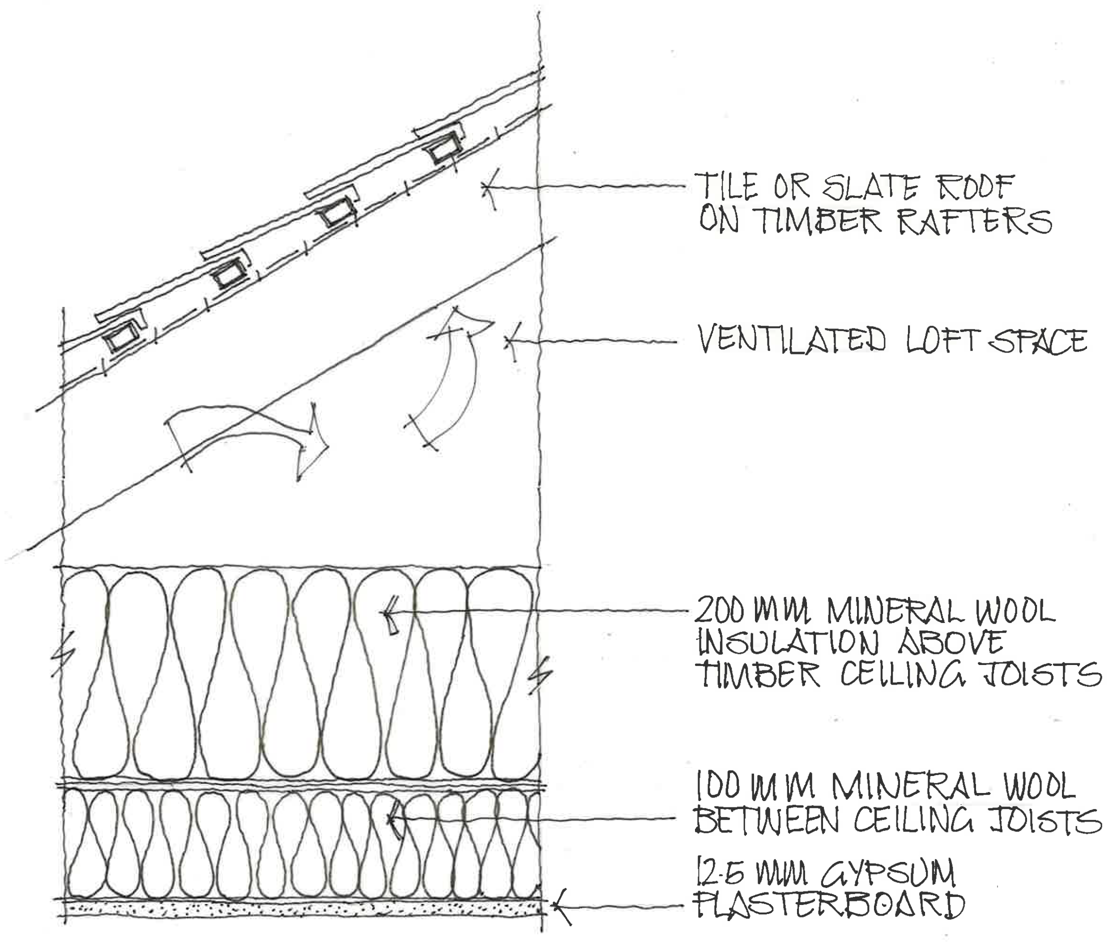


Figure 165: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

23.1. Build-up

23.1.1. WUFI Build-up (pre-retrofit)

<u>Build-Up:</u>

- Tile or slate roof *(considered outside of the WUFI build-up)*
- Ventilated loft space *(considered outside of the WUFI build-up)*

- 100mm mineral wool insulation (λ = 0.040 W/m.K) in between timber joists
- 12.5mm gypsum plasterboard

23.1.2. WUFI Build-up (post-retrofit)

Build-Up:

- Tile or slate roof *(considered outside of the WUFI build-up)*
- Ventilated loft space *(considered outside of the WUFI build-up)*
- 200mm mineral wool insulation (λ = 0.040 W/m.K) installed continuously above the timber joists
- 100mm mineral wool insulation (λ = 0.040 W/m.K) in between timber joists
- 12.5mm gypsum plasterboard

The build-up of R17 is identical to Part L case in N7 of *Using numerical simulation to assess moisture risk in new constructions* report (Cold pitched roof), with a slight variation in the thickness of the continuous insulation layer installed above the timber joists. As this modelling work is assessing qualitatively the impact of different measures on the hygrothermal performance of each typology, this slight difference in insulation thickness does not have any consequential effect on the results.

The only other difference between the two typologies is the timing of the installation of the continuous insulation layer. For N17, the continuous insulation layer is installed simultaneously to the rest of the roof construction; whereas for R17, the continuous insulation layer is retrofitted above the timber joists at ceiling level.

As part of the WUFI modelling process (in Section 3.4 of this report), a pre-retrofit build-up is supposed to be run to determine equilibrium levels. However, the pre-retrofit build-up for R17 is a slightly insulated roof, with a waterproof roof covering (tiles or slates). Because of the waterproof roof covering, the other materials present in the pre-retrofit build-up are not exposed to wind-driven rain. These materials are also not heavy weight materials. Therefore, it is not 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.

As no equilibrium model is required for R17, the initial conditions in the R17 WUFI model are identical to the N17 WUFI model. As a result, both R17 and N17 have the same WUFI input data and therefore share the same results, despite the difference in the timing of the installation of the continuous insulation layer. For these reasons, no baseline or sensitivity modelling is performed on this typology and please refer to Using numerical simulation to assess moisture risk in new constructions reportfor the results and analysis of typology N17 (Section 20).

24. Typology R18.1: Warm pitched roof - uninsulated Retrofit Measure: Insulation below rafters

The R18.1 typology is an uninsulated warm roof, i.e. a timber rafter structure, prior to retrofit. The retrofit measure is to insulate internally to the structure with closed-cell insulation.

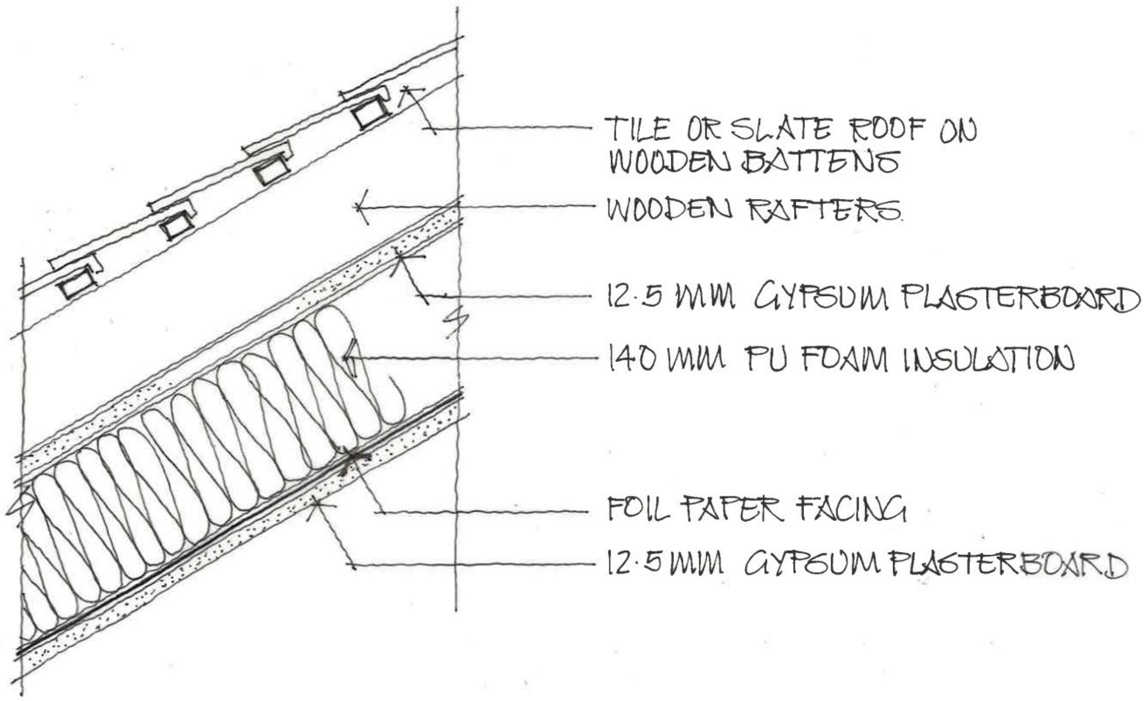


Figure 166: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

24.1. Assessment Method

Current prescriptive guidance in BS 5250 (2011) (paragraph H.5.3) states that *'in warm pitched roofs with a low resistance underlay, and AVCL should be provided at ceiling line. Where the external covering (such as fibre cement slates) is relatively airtight, there is a risk of interstitial condensation forming on the underside of the underlay and the external covering. To avoid that risk, the batten space should be vented'*.

To follow this prescriptive guidance, the void above the insulation is ventilated to the outside, to allow any moisture present in the void to be removed. This means that the roof covering 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 existing gypsum board to the internal finish.

The build-up does not contain very porous materials. In addition, the modelled build-up is not directly exposed to the elements (rain, wind and solar radiation), as the roof covering is acting as a protection layer. Therefore, the BS EN ISO 13788 (2012) assessment method should provide valid results for this typology.

The results by the Glaser method show that this build-up is considered a 'safe' build-up, with no risk of interstitial condensation, if the rafters are well ventilated. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

24.2. Build-up

24.2.1. WUFI Build-up (pre-retrofit)

Build-Up:

- Tile or slate roof *(considered outside of the WUFI build-up)*
- Ventilated air gap in between wooden battens *(considered outside of the WUFI build-up)*
- Roof breather membrane *(considered outside of the WUFI build-up)*
- Ventilated air gap in between wooden rafters *(considered outside of the WUFI build-up)*
- 12.5mm gypsum plasterboard

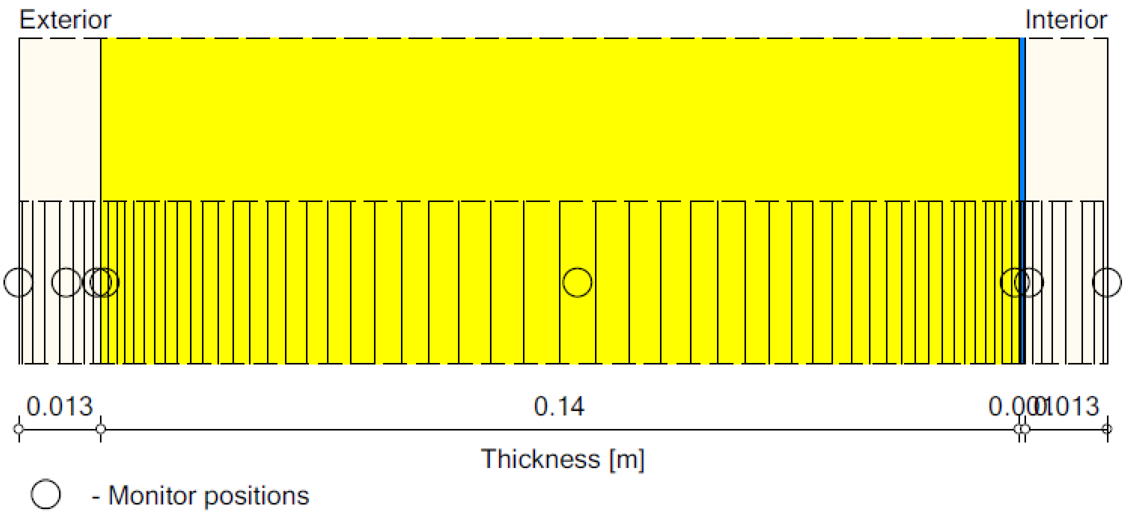
24.2.2. Initial Conditions

The materials present in the pre-retrofit build-up are not exposed to wind-driven rain and are not heavy weight materials. Therefore, it is not 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.

24.2.3. WUFI Build-up (post-retrofit)

Build-Up:

- Tile or slate roof *(considered outside of the WUFI build-up)*
- Ventilated air gap in between wooden battens *(considered outside of the WUFI build-up)*
- Roof breather membrane *(considered outside of the WUFI build-up)*
- Ventilated air gap in between wooden rafters *(considered outside of the WUFI build-up)*
- 12.5mm gypsum plasterboard
- 140mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 12.5mm gypsum plasterboard



Materials:

	- Gypsum Board	0.013 m
	- *PU (heat cond.: 0,025 W/mK)	0.14 m
	- *Foil paper facing (sd = 14m) (unlocked)	0.001 m
	- Gypsum Board	0.013 m

<u>WUFI Input Parameters</u>

As the structure is considered as externally ventilated, both the roof covering, breather membrane and the ventilated air gap in between rafters are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the existing gypsum plasterboard layer) is exposed to different external conditions due to the outer roof covering 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:

- Solar gains are not taken into account (as the roof covering layer is protecting the external surface of the insulation)
- Similarly, rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)

24.3. Baseline Results

24.3.1. Baseline Cases

The 4 baseline cases are set across the four wind-driven rain exposure zones, meeting the part L U-value, as set out below.

Table 52: 4 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2	Case 5	Case 8	Case 11
Other	-	-	-	-

24.3.2. Critical Junction

In the pre-retrofit state, the build-up is protected from the elements, and does not present any moisture risks. However, the addition of closed-cell insulation on the inside of the existing structure means that moisture could get trapped at the new interface between the existing gypsum plasterboard and the retrofitted insulation, creating a critical junction.

24.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, i.e. on the cold side the retrofit insulation, between the existing gypsum plasterboard layer and the retrofitted insulation.

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).

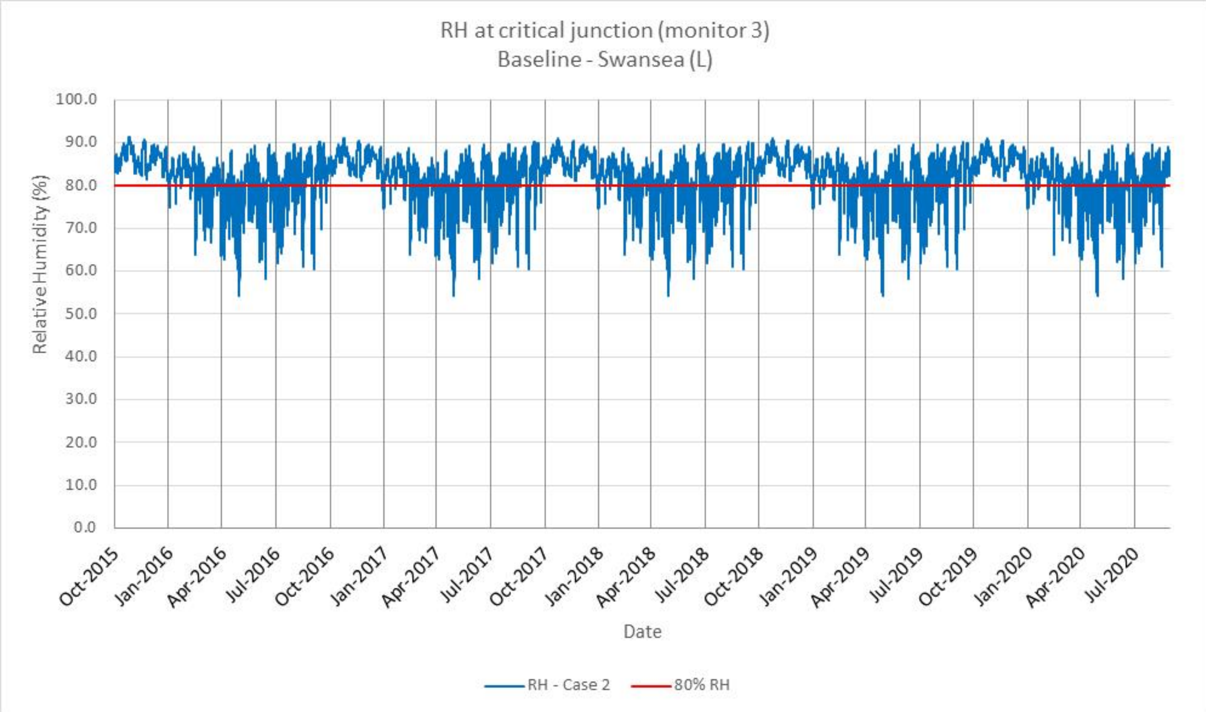


Figure 167: RH levels at critical junction for Case 2

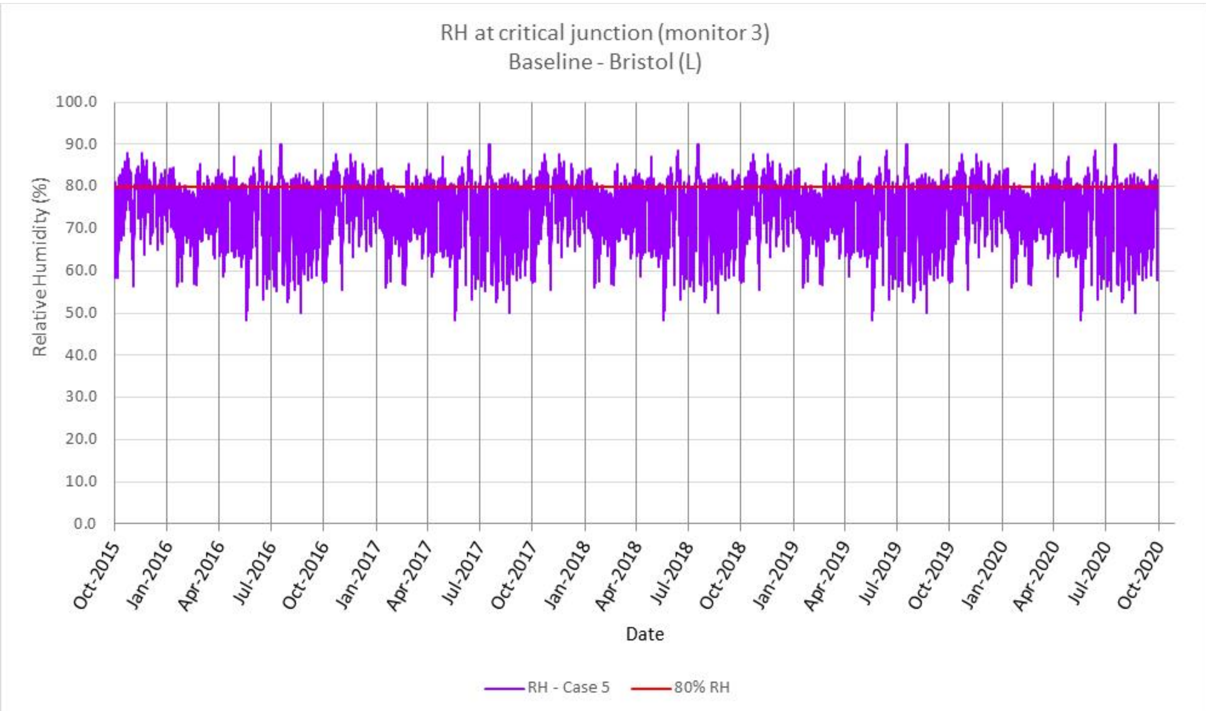


Figure 168: RH levels at critical junction for Case 5

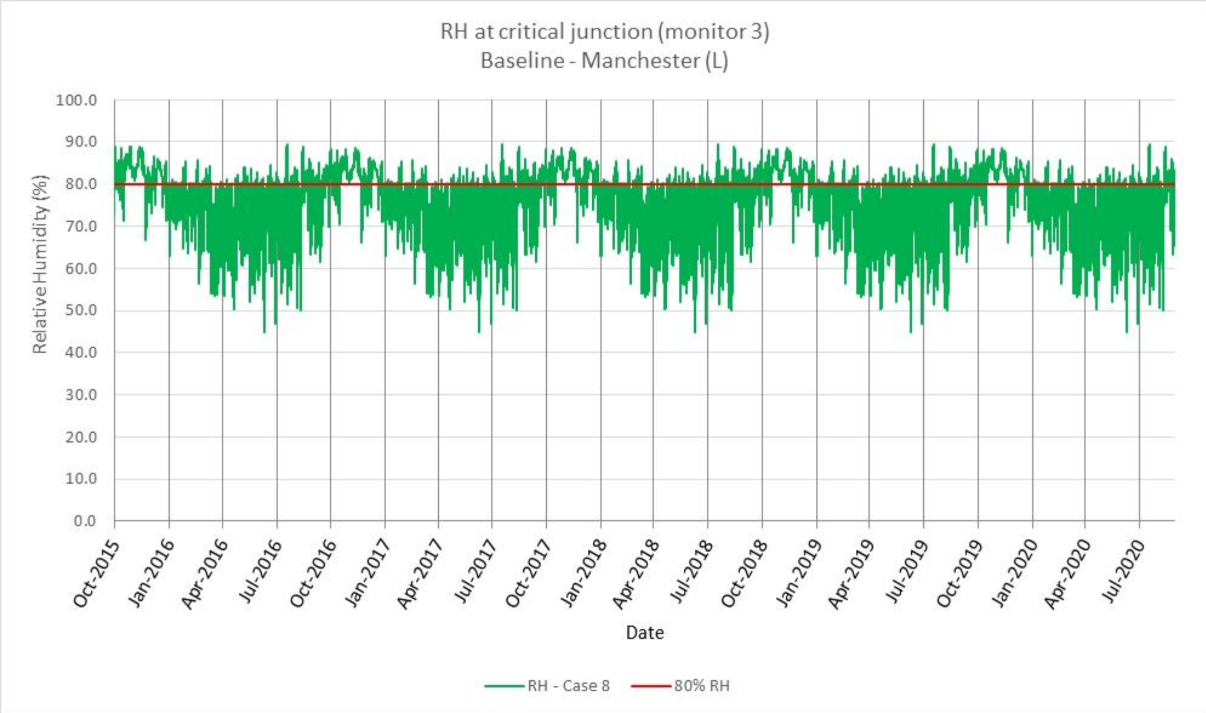


Figure 169: RH levels at critical junction for Case 8

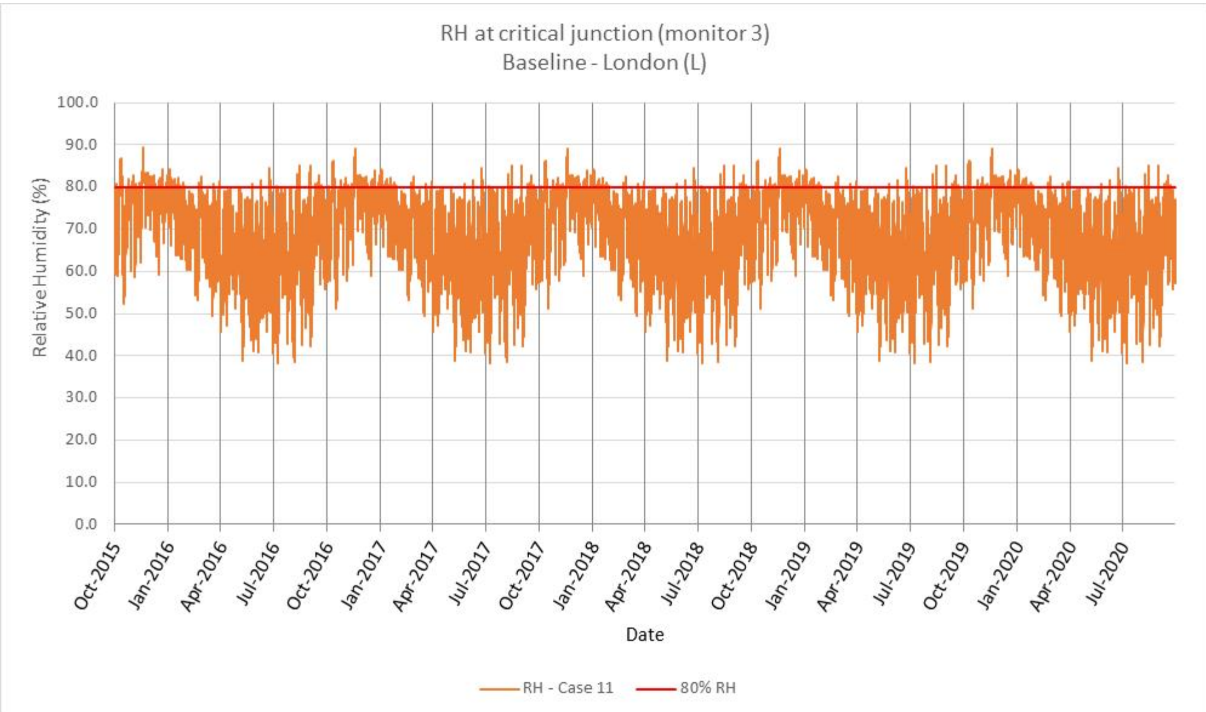


Figure 170: RH levels at critical junction for Case 11

24.3.4. Results Analysis

Moisture risk assessment criteria

The moisture risk assessment criterion is normally set at an 80% RH upper limit. This level is retained for this analysis, due to the presence of ‘fragile’ materials (i.e. gypsum plasterboard) at this junction.

All scenarios achieve equilibrium, which means that moisture does not accumulate over time. However, all cases are considered a ‘fail’ (with the exception of the case in Zone 1 - London, being ‘risky’) as RH levels at the critical junction are maintained above the 80% threshold for most of the year.

The suitable conditions for mould growth might also be present at this interface. Solid insulation boards are not highly flexible, which could allow for air to be present behind the insulation. The plasterboard layer is also adequate food for mould growth. And, despite the fact that RH levels are higher in winter, RH levels are above the 80% threshold regularly during the summer season, during which the temperature is adequate at this interface for mould growth.

These results are summarised in the table below.

<u>Results</u>

Table 53: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Equilibrium	n/a	n/a	n/a	n/a
Part L	Case 2 Fail	Case 5 Fail	Case 8 Fail	Case 11 Risky
Other	-	-	-	-

<u>Effects of exposure zones</u>

The effect of wind-driven rain exposure zones appears to play some role on the hygrothermal performance of the build-up, despite this build-up being considered not exposed to wind-driven rain. Indeed, the higher external RH levels in the more exposed zones (Zones 2, 3 and 4) lead to higher than recommended RH levels at the critical junction, and therefore cases being considered a ‘fail’. In contrast, the better external conditions experienced in Zone 1 - London are sufficiently favourable to reduce the risk identified with this retrofit measure.

24.3.5. Conclusions – Baseline

These findings agree somewhat with the findings from the BS EN ISO 13788 (2012), in the fact that no interstitial condensation is occurring at the critical junction. However, the BS EN ISO 13788 (2012) calculation gives a false comfort, stating that the build-up is ‘safe’, when the WUFI modelling shows that, in most of the zones, RH levels at the critical junction are kept relatively high and could lead to mould growth.

- This build-up is sheltered from the elements and externally ventilated with warm side AVCL, so safe from condensation in theory (BS EN ISO 13788)
- BS EN ISO 13788 calculations (‘safe’) and WUFI modelling (‘fail’) not in agreement – but there are limitations to WUFI modelling (ventilated void)
- High impact of ventilation in void (refer to other typologies)
- Low / medium impact of exposure zones (mould growth risk in most exposure zones)

24.4. Sensitivity Analysis – Change in Material [Cases X.d]: Removal of existing ceiling and addition of rigid insulation between rafters

Typical retrofitting of an existing pitched roof to meet Part L1B requirements also requires minimising the reduction in internal space. As such, the existing gypsum plasterboard ceiling is often removed first. Closed-cell insulation is then placed between rafters (typically 50-100mm) with a ventilated layer maintained to the outside the insulation layer (minimum 25mm as per Building Regulations). A continuous layer of closed cell insulation is finally installed below the rafters (typically 50-100mm) with a new plasterboard ceiling.

24.4.1. Conclusions – Sensitivity Analysis Cases X.d

The construction detailed in the previous paragraph is identical to the one modelled in the N18 typology in the Using numerical simulation to assess moisture risk in new constructions report. This was shown to be “safe” in all baseline cases modelled. Therefore, this retrofit construction is also considered to be ‘safe’ and is preferable to the approach taken in the baseline retrofit model in R18.1. Further sensitivity analysis done on the N18 typology also applies to this retrofit construction, regarding the use of an AVCL and the need to consider ABIS conditions. Please refer to the Using numerical simulation to assess moisture risk in new constructions report for more details (section 21).

24.5. Conclusions

- This build-up is sheltered from the elements and externally ventilated, with warm side AVCL, so no condensation in theory
- No critical junction and there are limitations of WUFI modelling (for ventilated void)
- Unsafe/risky results at monitored junction leading to potential mould growth
- As per N18, the safer build up is to remove the existing ceiling and insulate between and below the rafters
- As per N18

  - there is high impact of maintaining ventilation in void (refer to other typologies),
  - there is a low impact of exposure / orientation
  - there is a low impact of use of foil-backed insulations underneath the rafters

25. Typology R18.2: Warm pitched roof - uninsulated Retrofit Measure: Insulation between and below

The R18.2 typology is a pitched roof that is uninsulated prior to retrofit. The retrofit measure is to install insulation in between and below the timber rafters, thus making R18.2 a warm pitched roof.

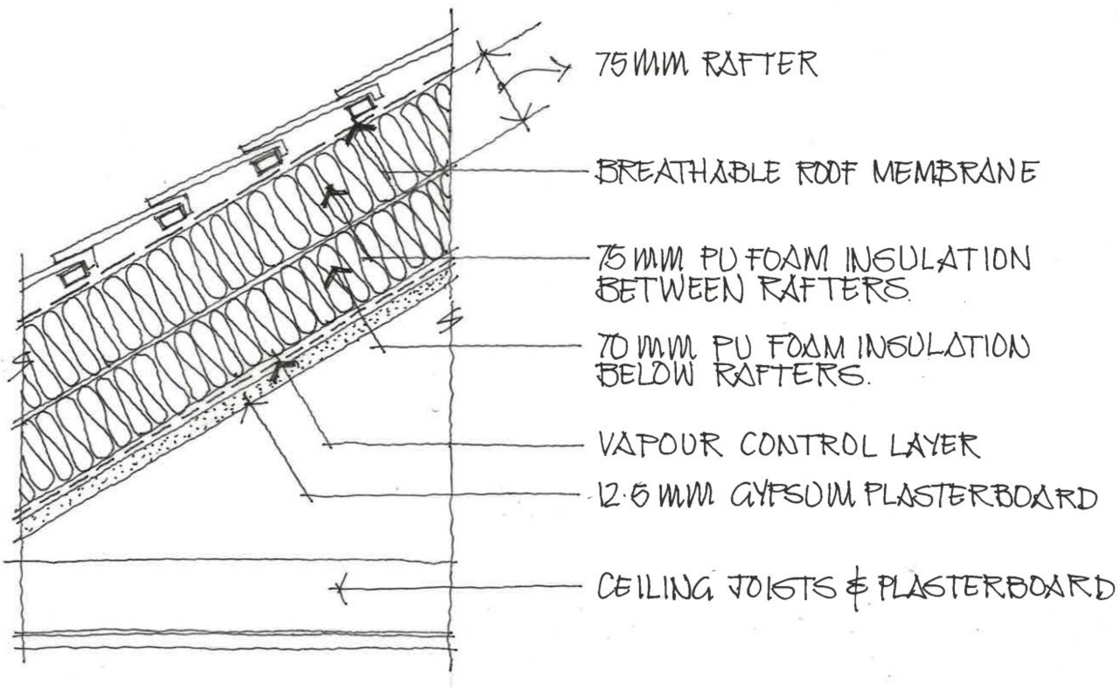


Figure 171: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

25.1. Build-up

25.1.1. WUFI Build-up (pre-retrofit)

<u>Build-Up:</u>

- Tile or slate roof *(considered outside of the WUFI build-up)*
- Ventilated air layer *(considered outside of the WUFI build-up)*
- Breathable roof membrane (sd = 0.04m)
- 100mm ventilated timber rafters
- 12.5mm gypsum plasterboard

25.1.2. WUFI Build-up (post-retrofit)

<u>Build-Up:</u>

- Tile or slate roof (considered outside of the WUFI build-up)
- Ventilated air layer (considered outside of the WUFI build-up)
- Breathable roof membrane (sd = 0.04m)
- 75mm PU foam insulation (λ = 0.025 W/m.K) in between 100mm timber rafters (leaving a 25mm ventilated gap between the breathable roof membrane and the upper side of the retrofitted insulation)
- 70mm PU foam insulation (λ = 0.025 W/m.K) installed continuously below timber rafters
- 1mm AVCL (sd = 2m)
- 12.5mm gypsum plasterboard

The build-up of R18.2 is identical to Part L case in N18 of Using numerical simulation to assess moisture risk in new constructions report (Warm pitched roof), with a slight variation in the thickness of the continuous insulation layer installed below the timber rafters. As this modelling work is assessing qualitatively the impact of different measures on the hygrothermal performance of each typology, this slight difference in insulation thickness does not have any consequential effect on the results.

The only other difference between the two typologies is the timing of the installation of the insulation layers. For N18, the insulation is installed simultaneously to the rest of the roof construction; whereas for R18.2, both insulation layers are retrofitted afterwards, between and below the existing roof structure.

As part of the WUFI modelling process (in Section 3.4 of this report), a pre-retrofit build-up is supposed to be run to determine equilibrium levels. However, the pre-retrofit build-up for R18.2 is an uninsulated pitched roof with a waterproof roof covering (tiles or slates). Because of the waterproof roof covering, the other materials present in the pre-retrofit build-up are not exposed to wind-driven rain. These materials are also not heavy weight materials. Therefore, it is not 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.

As no equilibrium model is required for R18.2, the initial conditions in the R18.2 WUFI model are identical to the N18 WUFI model. As a result, both R18.2 and N18 have the same WUFI input data and therefore share the same results, despite the difference in the timing of the installation of the insulation layers. For these reasons, no baseline or sensitivity modelling is performed on this typology and please refer to Using numerical simulation to assess moisture risk in new constructions report for the results and analysis of typology N18 (Section 21).

26. Typology R19: Warm flat timber roof Retrofit Measure: insulation above

The R19 typology is a flat timber roof that is uninsulated prior to retrofit. The retrofit measure is to remove the waterproof roof covering, replace the ply deck if required, install a continuous layer of insulation above the ply deck, thus making R19 a warm flat roof.

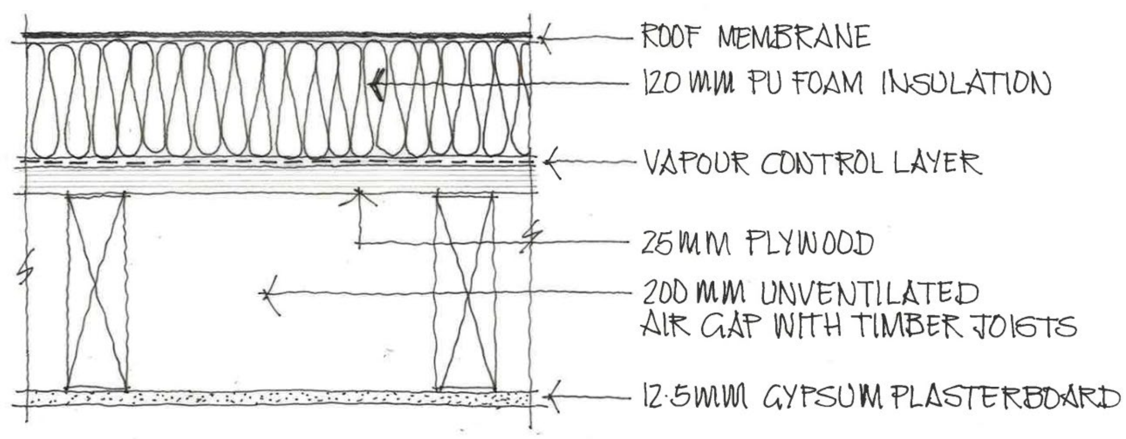


Figure 172: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

26.1. Build-up

26.1.1. Roof membranes

There are many products available to act as waterproof covering on flat roofs. As this work is generic, a decision was taken to model single ply roof membranes for all flat roof typologies (R19 to R22), as this is a currently more commonly used material, compared to other waterproof coverings.

Research was done to obtain the typical characteristics (sd-value) of commonly used roof membranes currently used in the industry. Product research showed that typical sd-values for roof membranes range from 50 to 150m. Therefore, an average value of sd = 100m was chosen for the typical characteristics of the roof membrane used in this modelling work for all flat roof typologies (R19 to R22).

We have not modelled all solutions as this is beyond the scope of the existing project. However, it is worth noting that the modelling results are valid for any roof covering with similar characteristics (due to the convention in WUFI to model any 'membrane' (such as DPM, ACVL, roof membrane, bituminous felt, etc.) with a 1mm thickness and its associated sd-value. This convention allows the correct water vapour diffusion resistance factor μ to be easily obtained (with μ being the sd-value divided by the thickness, with the thickness being 1mm).

With the use of a roof membrane in the WUFI modelling, it is assumed that the existing roof covering present in the pre-retrofit build-up is removed prior to the installation of the retrofit measure, and then reinstalled adequately in a new location of the post-retrofit build-up.

It is worth noting that, if other roof covering types (with similar sd-value) are used, such as bitumen felt, removing this roof covering prior to the retrofit measure installation might not always be possible. This would then need to be taken into account and new modelling would be required, as retaining a water vapour barrier which will be sandwiched between existing and newly installed materials could have a significant impact on the hygrothermal performance of the build-up.

26.1.2. WUFI Build-up (pre-retrofit)

Build-Up:

- 1mm roof membrane (sd = 100m)
- 25mm plywood board
- 200mm unventilated air gap in between timber joists
- 12.5mm gypsum plasterboard

26.1.3. WUFI Build-up (post-retrofit)

Build-Up:

- 1mm roof membrane (sd = 100m)
- 80mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm AVCL (sd = 2m)
- 25mm plywood board
- 200mm unventilated air gap in between timber joists
- 12.5mm gypsum plasterboard

The build-up of R19 is identical to Part L case in N19 of Using numerical simulation to assess moisture risk in new constructions report (Warm flat roof - timber) with a slight variation in the thickness of the insulation layer. As this modelling work is assessing qualitatively the impact of different measures on the hygrothermal performance of each typology, this slight difference in insulation thickness does not have any consequential effect on the results.

The only other difference between the two typologies is the timing of the installation of the insulation layer. For N19, the insulation is installed simultaneously to the rest of the roof construction; whereas for R19, the insulation is retrofitted above the existing roof structure.

As part of the WUFI modelling process (in Section 3.4 of this report), a pre-retrofit build-up is supposed to be run to determine equilibrium levels. However, the pre-retrofit build-up for R19 is an uninsulated roof with a waterproof roof membrane. Because of the waterproof roof membrane, the other materials present in the pre-retrofit build-up are not exposed to wind-driven rain. These materials are also not heavy weight materials. Therefore, it is not 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.

As no equilibrium model is required for R19, the initial conditions in the R19 WUFI model are identical to the N19 WUFI model. As a result, both R19 and N19 have the same WUFI input data and therefore share the same results, despite the difference in the timing of the installation of the insulation layer. For these reasons, no baseline or sensitivity modelling is performed on this typology and please refer to Using numerical simulation to assess moisture risk in new constructions reportfor the results and analysis of typology N19 (Section 22).

27. Typology R20: Cold flat roof Retrofit Measure: insulation below

The R20 typology is a ‘cold roof’ with a timber deck prior to retrofit. The retrofit measure is to install insulation below the timber deck.

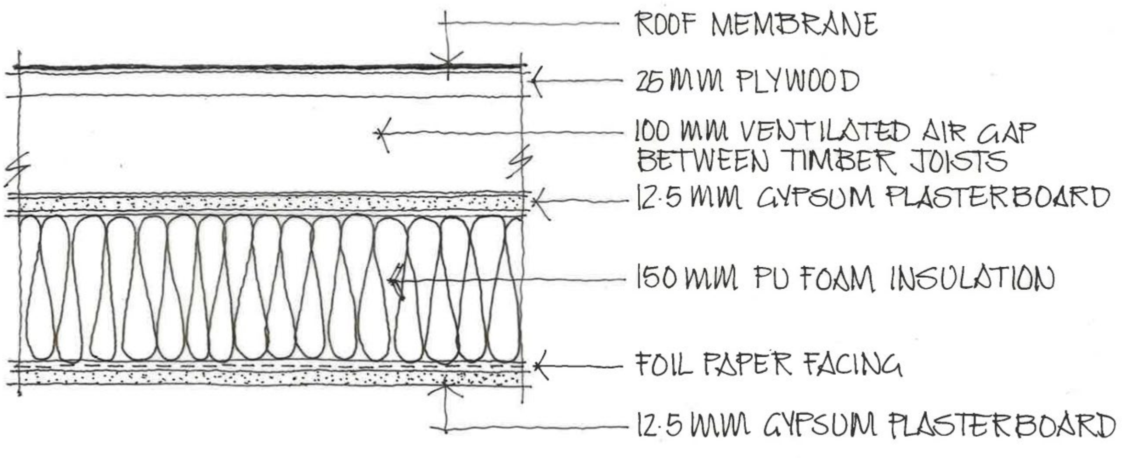


Figure 173: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

27.1. Build-up

27.1.1. WUFI Build-up (pre-retrofit)

<u>Build-Up:</u>

- 1mm roof membrane (sd = 100m) *(considered outside of the WUFI build-up)*
- 25mm plywood deck *(considered outside of the WUFI build-up)*
- 100mm ventilated air layer in between timber joists *(considered outside of the WUFI build-up)*
- 12.5mm gypsum plasterboard

27.1.2. WUFI Build-up (post-retrofit)

Build-Up:

- 1mm roof membrane (sd = 100m) *(considered outside of the WUFI build-up)*
- 25mm plywood deck *(considered outside of the WUFI build-up)*
- 100mm ventilated air layer in between timber joists *(considered outside of the WUFI build-up)*
- 12.5mm gypsum plasterboard
- 150mm PU foam insulation (λ = 0.025 W/m.K) below timber joists
- 1mm foil paper facing
- 12.5mm gypsum plasterboard

As all layers outside of the ventilated air gap (between timber joists) are considered ‘outside’ and therefore are not accounted / modelled in the WUFI model. Due to these modelling conventions / limitations, the R20 build-up is identical to the R18.1 build-up of this report (warm pitched roof – uninsulated – with insulation retrofitted below the rafters), despite a different roof covering and a slight variation in the thickness of the insulation layer. As this modelling work is assessing qualitatively the impact of different measures on the hygrothermal performance of each typology, this slight difference in insulation thickness does not have any consequential effect on the results.

The only other difference between the two typologies is the inclination of the build-up (35° for R18.1 – pitched roof – and 2° for R20 – flat roof). However, as both typologies are fully protected from wind-driven rain (due to their respective roof covering), this difference in orientation between the two typologies will not lead to different WUFI modelling results.

For these reasons, no baseline or sensitivity modelling is performed on this typology and please refer to R18.1.

28. Typology R21: Warm flat concrete roof Retrofit Measure: insulation above

The R21 typology is a flat concrete roof that is uninsulated prior to retrofit. The retrofit measure is to install insulation continuously above the dense structure (concrete).

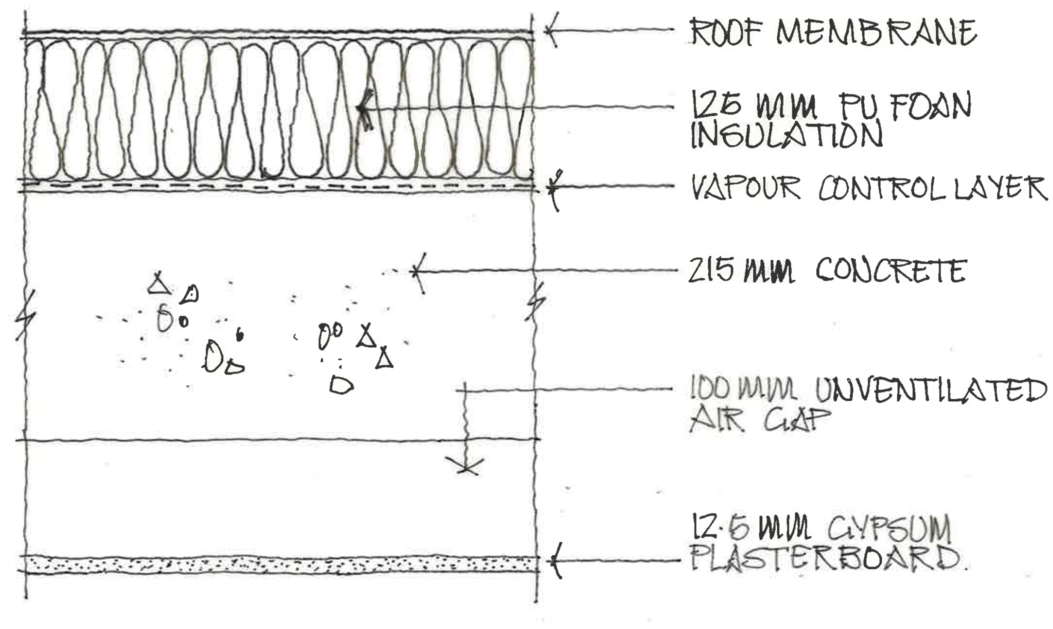


Figure 174: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

28.1. Build-up

28.1.1. WUFI Build-up (pre-retrofit)

Build-Up:

- 1mm roof membrane (sd = 100m)
- 215mm concrete structure
- 100mm unventilated air gap with metal ceiling rails
- 12.5mm gypsum plasterboard

28.1.2. WUFI Build-up (post-retrofit)

<u>Build-Up:</u>

- 1mm roof membrane (sd = 100m)
- 125mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm AVCL (sd = 2m)
- 215mm concrete structure
- 100mm unventilated air gap with metal ceiling rails
- 12.5mm gypsum plasterboard

The build-up of R21 is identical to the Part L case in N21 of Using numerical simulation to assess moisture risk in new constructions report (Warm roof - concrete), with a slight variation in the thickness of the insulation layer. As this modelling work is assessing qualitatively the impact of different measures on the hygrothermal performance of each typology, this slight difference in insulation thickness does not have any consequential effect on the results.

The only other difference between the two typologies is the timing of the installation of the insulation layer. For N21, the insulation is installed simultaneously to the rest of the roof construction; whereas for R21, the insulation is retrofitted above the existing roof structure.

As part of the WUFI modelling process (in Section 3.4 of this report), a pre-retrofit build-up is supposed to be run to determine equilibrium levels. However, the pre-retrofit build-up for R21 is an uninsulated concrete roof with a waterproof roof covering (here being bituminous felt). Because of the waterproof roof covering, the materials present in the pre-retrofit build-up are not exposed to wind-driven rain. Consequently, the concrete layer present in the pre-retrofit build-up is drier than it would be in a new-build construction scenario, as it has had enough time to dry to the inside of the property (assuming adequate temperature and RH levels internally). This means that using default values for the initial moisture contents of materials (like it is done in N21 of Using numerical simulation to assess moisture risk in new constructions report) is modelling is a worse scenario, compared to the pre-retrofit model described in this typology. Therefore, it is not 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.

As no equilibrium model is required for R21, the initial conditions in the R21 WUFI model are identical to the N21 WUFI model. As a result, both R21 and N21 have the same WUFI input data and therefore share the same results, despite the difference in the timing of the installation of the insulation layer. For these reasons, no baseline or sensitivity modelling is performed on this typology and please refer to Using numerical simulation to assess moisture risk in new constructions reportfor the results and analysis of typology N21 (Section 24).

It must also be noted that the pre-retrofit model (an uninsulated concrete roof with a waterproof covering installed straight onto the concrete layer) is considered a very unusual build-up, which is unlikely to be found in practice. This fact then supports the decision not to run of a pre-retrofit equilibrium model and focus instead on the new-build version of this build-up.

29. Typology R22: Inverted flat concrete roof Retrofit Measure: insulation above

The R22 typology is an inverted flat roof (dense structure) that is uninsulated prior to retrofit. The retrofit measure is to install insulation continuously above the dense structure (concrete) and roof waterproof covering layer.

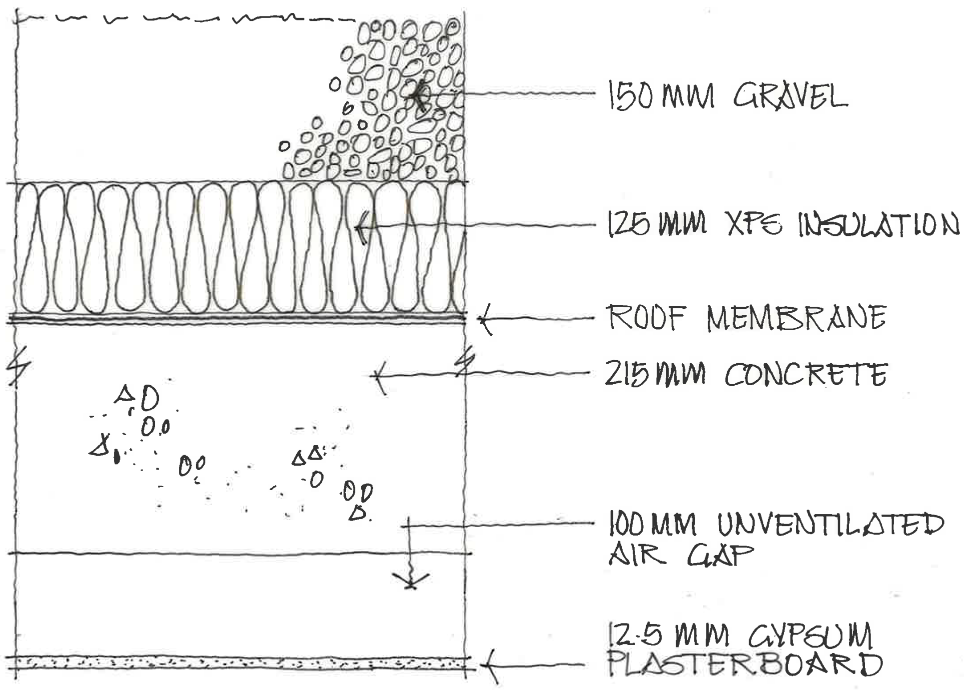


Figure 175: Illustration of the build-up of the typology with retrofit measure installed (Part L case)

29.1. Build-up

29.1.1. WUFI Build-up (pre-retrofit)

<u>Build-Up:</u>

- 150mm gravel
- 1mm roof membrane (sd = 100m)
- 215mm concrete structure
- 100mm unventilated air gap with metal ceiling rails
- 12.5mm gypsum plasterboard

29.1.2. WUFI Build-up (post-retrofit)

Build-Up:

- 150mm gravel
- 125mm XPS insulation (λ = 0.030 W/m.K) modelled in three layers as suggested by the WUFI software (using the XPS surface skin and XPS core materials)
- 1mm roof membrane (sd = 100m)
- 215mm concrete structure
- 100mm unventilated air gap with metal ceiling rails
- 12.5mm gypsum plasterboard

The build-up of R22 is identical to the Part L case in N22 of Using numerical simulation to assess moisture risk in new constructions report (Inverted roof - concrete), with a slight variation in the thickness of the insulation layer. As this modelling work is assessing qualitatively the impact of different measures on the hygrothermal performance of each typology, this slight difference in insulation thickness does not have any consequential effect on the results.

The only other difference between the two typologies is the timing of the installation of the insulation layer. For N22, the insulation is installed simultaneously to the rest of the roof construction; whereas for R22, the insulation is retrofitted above the existing roof structure.

As part of the WUFI modelling process (in Section 3.4 of this report), a pre-retrofit build-up is supposed to be run to determine equilibrium levels. However, the pre-retrofit build-up for R22 is an uninsulated concrete roof with a waterproof roof covering (here being a roof membrane). Because of the waterproof roof covering, the materials present in the pre-retrofit build-up are not exposed to wind-driven rain. Consequently, the concrete layer present in the pre-retrofit build-up is drier than it would be in a new-build construction scenario, as it has had enough time to dry to the inside of the property (assuming adequate temperature and RH levels internally). This means that using default values for the initial moisture contents of materials (like it is done in N22 of Using numerical simulation to assess moisture risk in new constructions report) is modelling is a worse scenario, compared to the pre-retrofit model described in this typology. Therefore, it is not 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.

As no equilibrium model is required for R22, the initial conditions in the R22 WUFI model are identical to the N22 WUFI model. As a result, both R22 and N22 have the same WUFI input data and therefore share the same results, despite the difference in the timing of the installation of the insulation layer. For these reasons, no baseline or sensitivity modelling is performed on this typology and please refer to Using numerical simulation to assess moisture risk in new constructions reportfor the results and analysis of typology N22 (Section 25).

It must also be noted that the pre-retrofit model (an uninsulated concrete roof with a waterproof covering installed straight onto the concrete layer) is considered a very unusual build-up, which is unlikely to be found in practice. This fact then supports the decision not to run of a pre-retrofit equilibrium model and focus instead on the new-build version of this build-up.

30. Connective Effects on Retrofit cases using THERM junction modelling

A working set of the most common Retrofit junctions was proposed in chapter 7 of the *Identification of common types of construction* report and these are shown in the table below. Since there are no ACDs available for Retrofit cases, these junctions have been chosen on the basis of the most common cases and critical scenarios.

Table 54: Retrofit junctions analysed

1	**Ground Floors**
1.1	Ground bearing floor / Solid wall - EWI and IWI
1.2	Ground floor suspended / Wall junction - EWI and IWI
1.3	Below DPC solid wall - EWI
2	**Windows**
2.1	Window head - cill - jamb / solid wall - EWI and IWI
3	**Upper Floors**
3.1	First floor edge with solid wall - IWI
3.2	Stair string - IWI
4	**Exposed Floors**
4.1	Exposed floor - EWI and IWI
4.2	Exposed floor inverted - EWI and IWI
4.3	Balcony or walkway support penetrates wall - EWI and IWI
5	**Eaves**
5.2	Eaves (insulation at flat ceiling level) - EWI
5.3	Eaves (insulation between / under rafter) - EWI and IWI
6	**Gable at roof junction**
6.1	Gable (insulation at ceiling level) - EWI and IWI
6.2	Gable (insulation at rafter level) - EWI and IWI
7	**Roof**
7.1	Cold roof insulation / external wall
7.2	Loft hatch
8	**Other**
8.1	External Meter boxes - EWI

The models built in THERM will analyse, where possible, the connective effects of insulating various elements which are retrofitted according to the requirements of AD L, and which are adjacent to uninsulated and insulated elements.

As with the scenarios previously modelled for New Buildings, the conditions set for the simulation are 20°C internal temperature (T_i) and 0°C external temperature (T_e), which means that for unsheltered elements all surface temperatures (T_{si}) should have a minimum temperature of 15°C to avoid mould risk. Sheltered elements such as underfloor voids are dealt with in the commentary for build-ups where these conditions apply.

30.1. Interstitial condensation risk

In any retrofit scenario where internal insulation is installed the surface of the insulated element will become cooler and the risk of interstitial condensation will arise. This risk is identified and modelled for building elements using WUFI. This section of analysis therefore is limited to identification of surface mould growth risk.

30.2. Risk categorisation

In order to aid interpretation the following categorisation is given to level of risk of mould growth depending on fRsi.

f_{Rsi}	Risk
below 0.6	very high risk
≤0.6 - 0.7	high risk
≤0.7 - 0.75	risk
≤0.75 - 0.85	low risk
above 0.85	very low risk

30.3. Thermal performance of junctions

This study is concerned only with moisture risk and is therefore not primarily concerned with thermal performance at junctions. Junctions are modelled as typically constructed and may exhibit high heat loss characteristics. Any new junction design will need to consider both of these aspects.

30.4.

It should be noted that there may be other technical considerations which may prevent the details shown being adopted. This analysis only relates to surface condensation.

31. Ground floors

A number of scenarios commonly found in existing building have been considered for this section; these have been analysed with a solid and suspended floor, with and without the below DPC insulation to mitigate the thermal bridge at the floor slab perimeter, with external or internal wall insulation. Additional cases have been simulated to check the corner temperature when the insulation at the wall and floor are not overlapping.

31.1. Ground bearing floor / Solid wall - EWI and IWI

31.1.1. Build-up - Uninsulated ground bearing floor with IWI (typology R8)

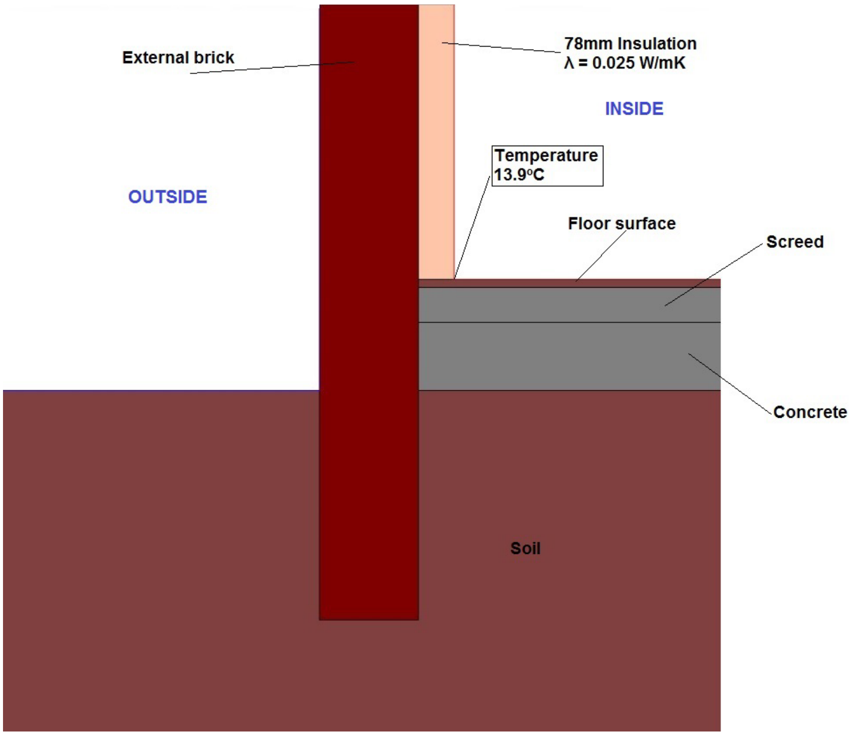


Figure 176: Junction between an uninsulated concrete ground floor and a wall insulated internally (typology R8) with no junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 13.9°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.70, which indicates a risk of mould growth at this junction.

31.1.2. Build-up - Insulated ground bearing floor (typology R2) with IWI (typology R8)

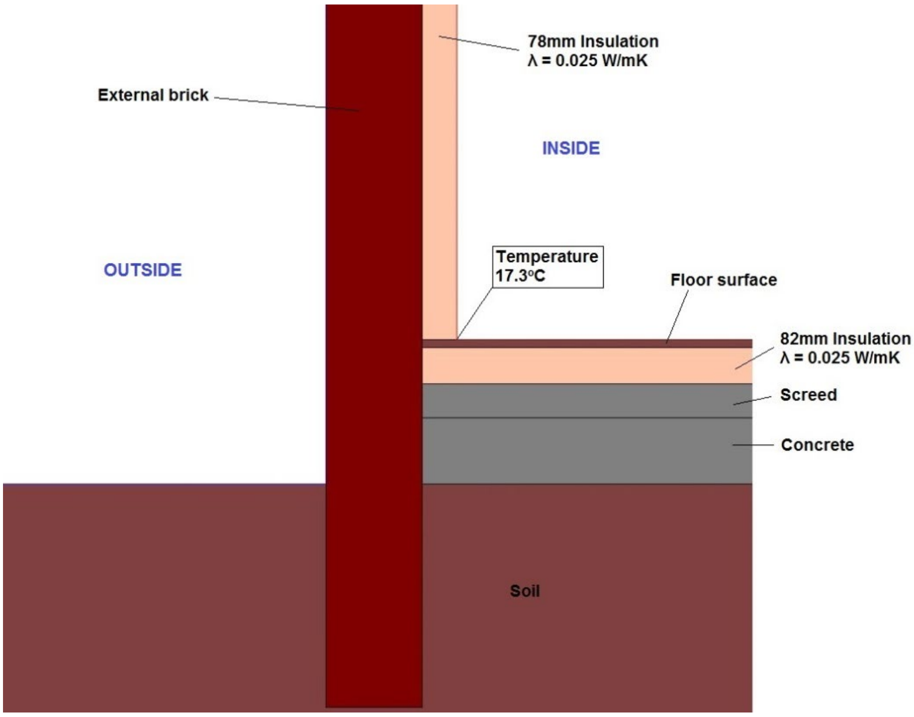


Figure 177: Junction between an insulated ground bearing floor (R2) and a wall insulated internally (R8) with no junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 17.3°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.87, which indicates a very low risk of mould growth.

31.1.3. Build-up - Uninsulated ground bearing floor with EWI (typology R9)

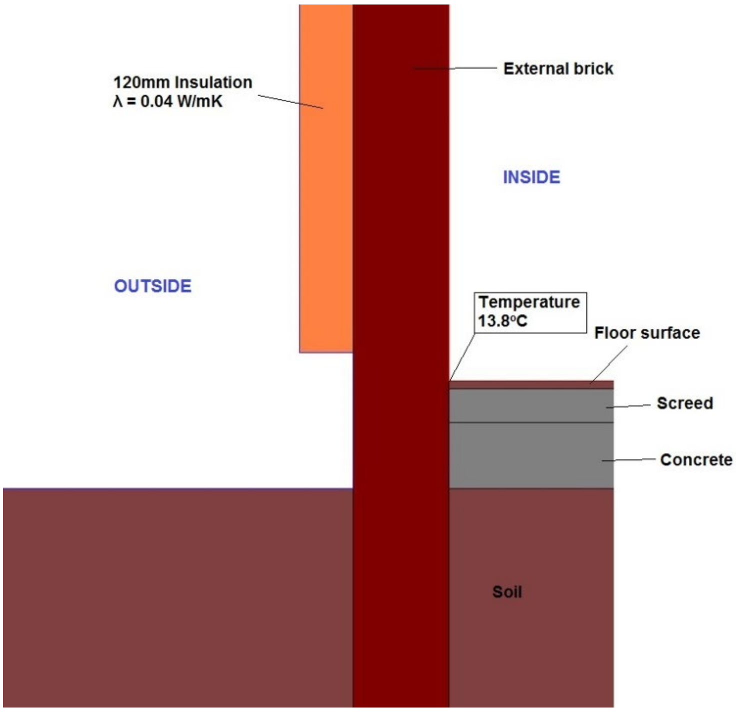


Figure 178: Junction between an uninsulated concrete ground floor and a wall insulated externally (typology R9) with no junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 13.8°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.69, which indicates a high risk of mould growth at this junction.

31.1.4. Build-up - Insulated ground bearing floor (typology R2) with EWI (typology R9)

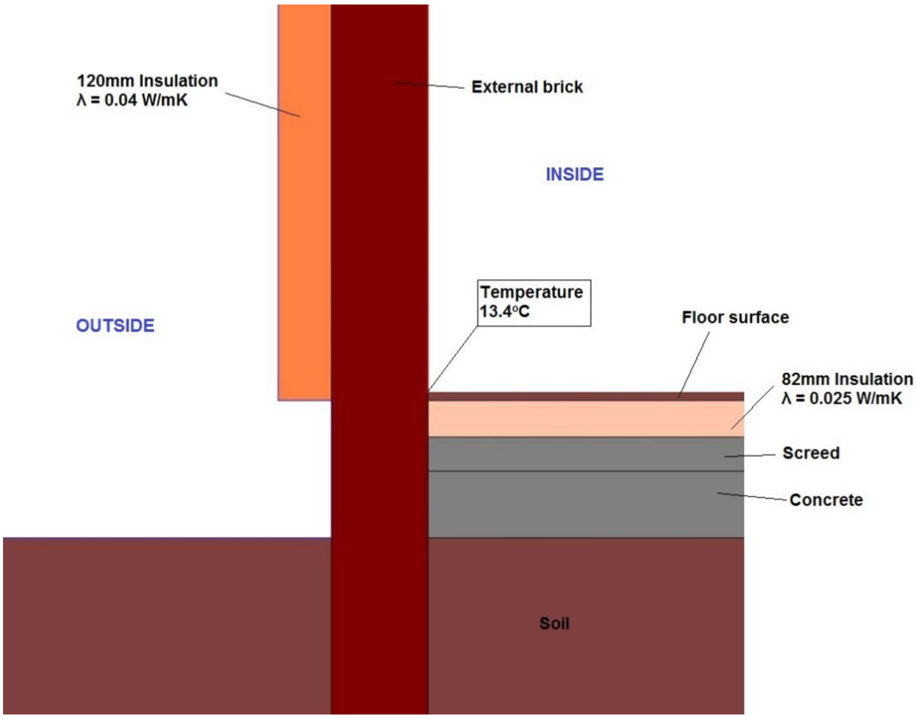


Figure 179: Junction between an insulated ground bearing floor (R2) and a wall insulated externally (R9) with no junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 13.4°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.61, which indicates a high risk of mould growth.

31.1.5. Conclusions

- The simplest construction solution for this junction type has a very high mould growth risk
- In the IWI scenario insulation at floor level helps mitigate moisture risk.
- In the EWI scenario insulation at floor level does not mitigate the moisture risk and worsens the situation, it is therefore not recommended.

31.1.6. Build-up - Uninsulated suspended floor with IWI (typology R8)

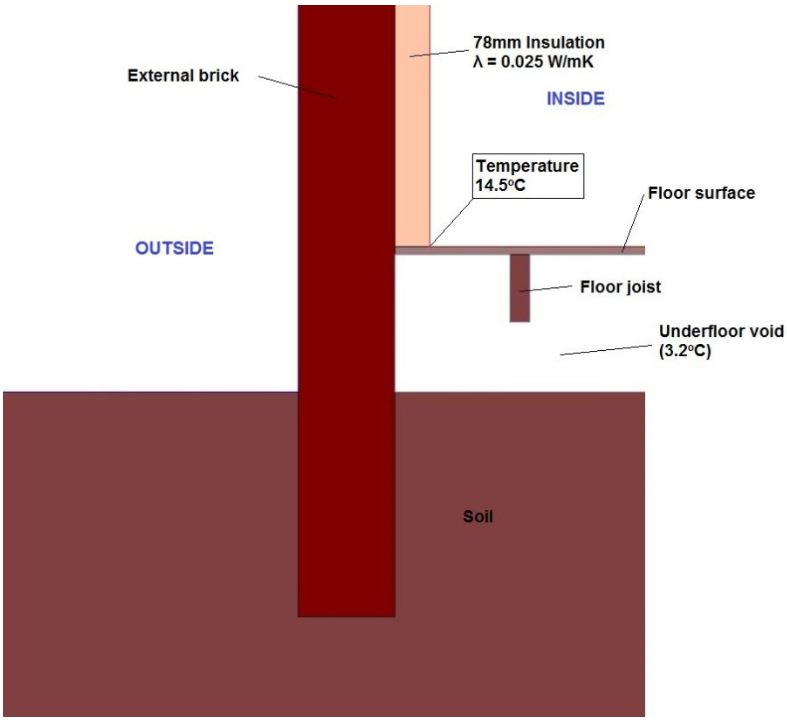


Figure 180: Junction between an uninsulated suspended ground floor and a wall with internal insulation (typology R8) with no junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 14.5°C at the junction corner. With an external temperature of 0°C and a temperature under floor of 3.2°C, the resultant f_{Rsi} is 0.67 which indicates a high risk of mould growth at this junction.

The lowest surface temperature of 9.9°C is found on the floor boards, away from the junction. This element, as a pre-retrofit structure has not been separately analysed.

31.1.7. Build-up - Insulated suspended floor (typology R1) with IWI (typology R8)

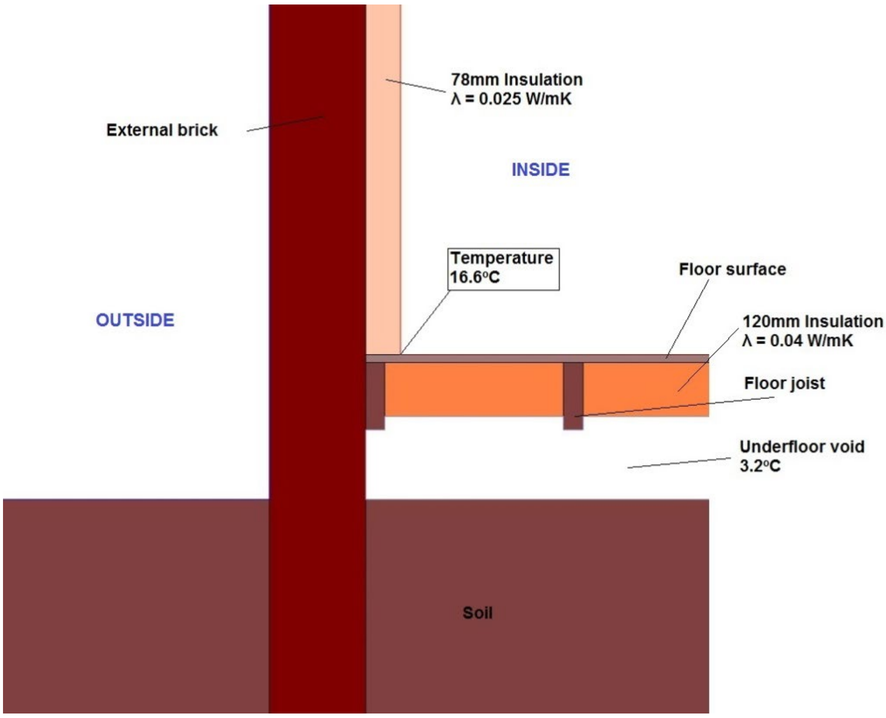


Figure 181: Junction between an insulated suspended ground floor (typology R1) and a wall with internal insulation (typology R8) with no junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 16.6°C at the junction corner. With an external temperature of 0°C and a temperature under floor of 3.2°C, the resultant f_{Rsi} is 0.8, which indicates a low risk of mould growth.

31.1.9. Build-up - Uninsulated suspended floor with EWI (typology R9)

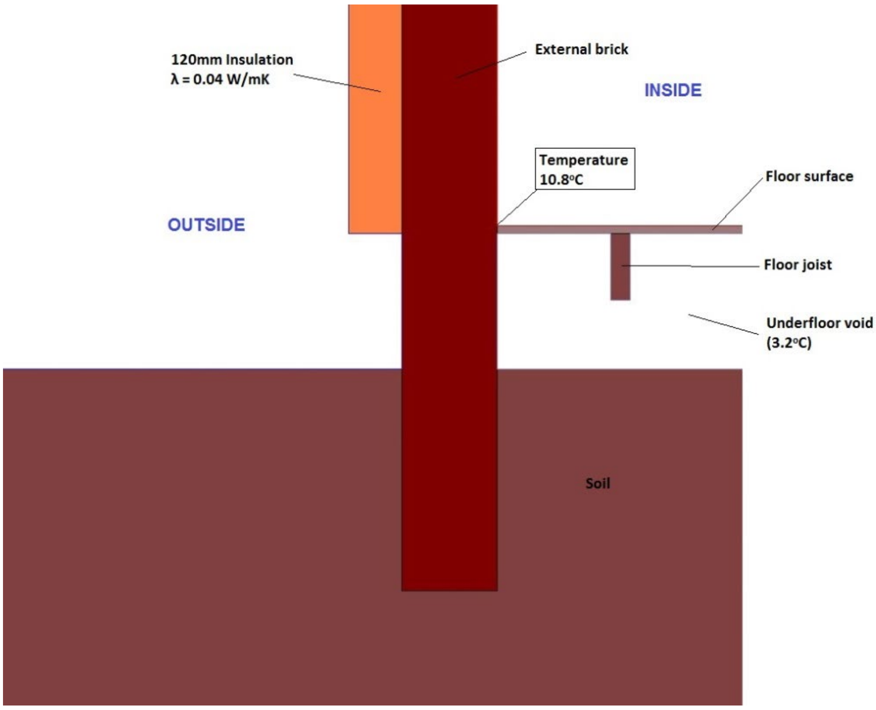


Figure 182: Junction between an uninsulated suspended ground floor and a wall with external insulation (typology R9) with no junction insulation

- Results Analysis

Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (T_{si}) is 10.8°C at the junction corner. With a temperature under floor of 3.2°C, the resultant f_{Rsi} is 0.45, which indicates a very high risk of mould growth at this junction.

The lowest surface temperature of 9.6°C is found on the floor boards, away from the junction. This element, as a pre-retrofit structure has not been separately analysed.

31.1.10. Build-up - Insulated suspended floor (typology R1) with EWI (typology R9)

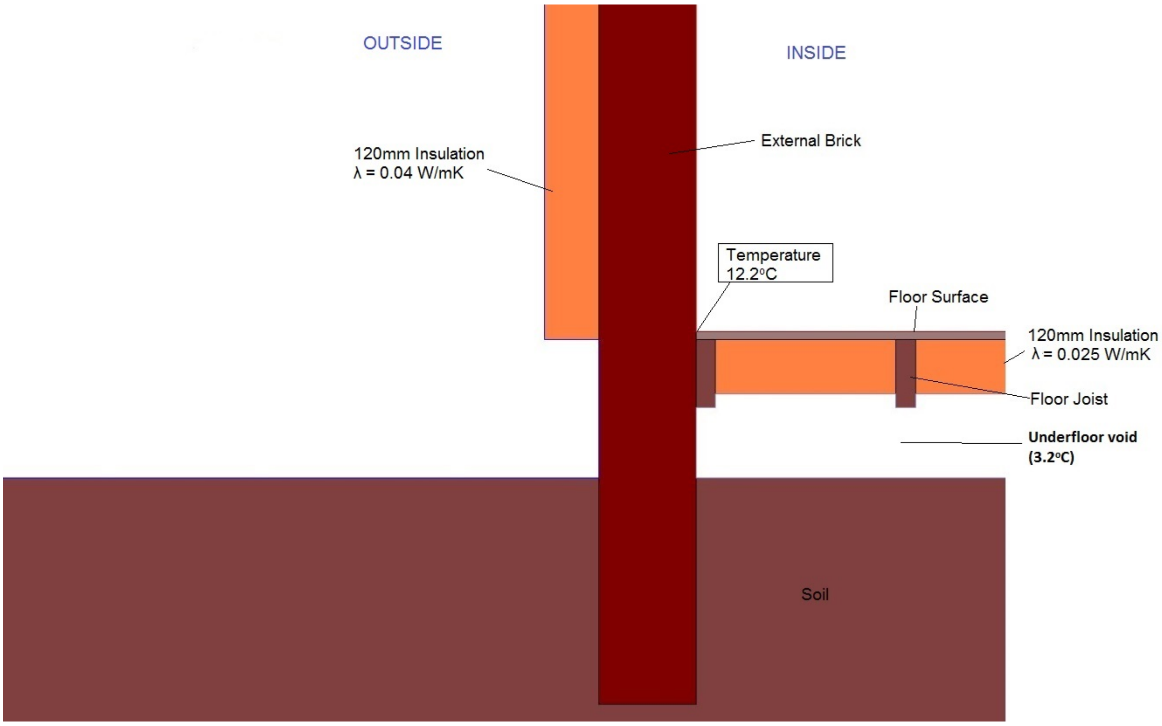


Figure 183: Junction between an insulated suspended ground floor (typology R1) and a wall with external insulation (typology R9) with no junction insulation

- Results Analysis

Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (T_{si}) is 12.2°C at the junction corner. With an external temperature of 0°C and a temperature under floor of 3.2°C, the resultant f_{Rsi} is 0.54, which indicates a high risk of mould growth at this junction.

31.1.11. Conclusions

- In this scenario floor insulation is recommended to reduce moisture risk.

31.2. Below DPC / Solid wall - EWI

31.2.1. Build-up - Uninsulated ground bearing floor with EWI (typology R9)

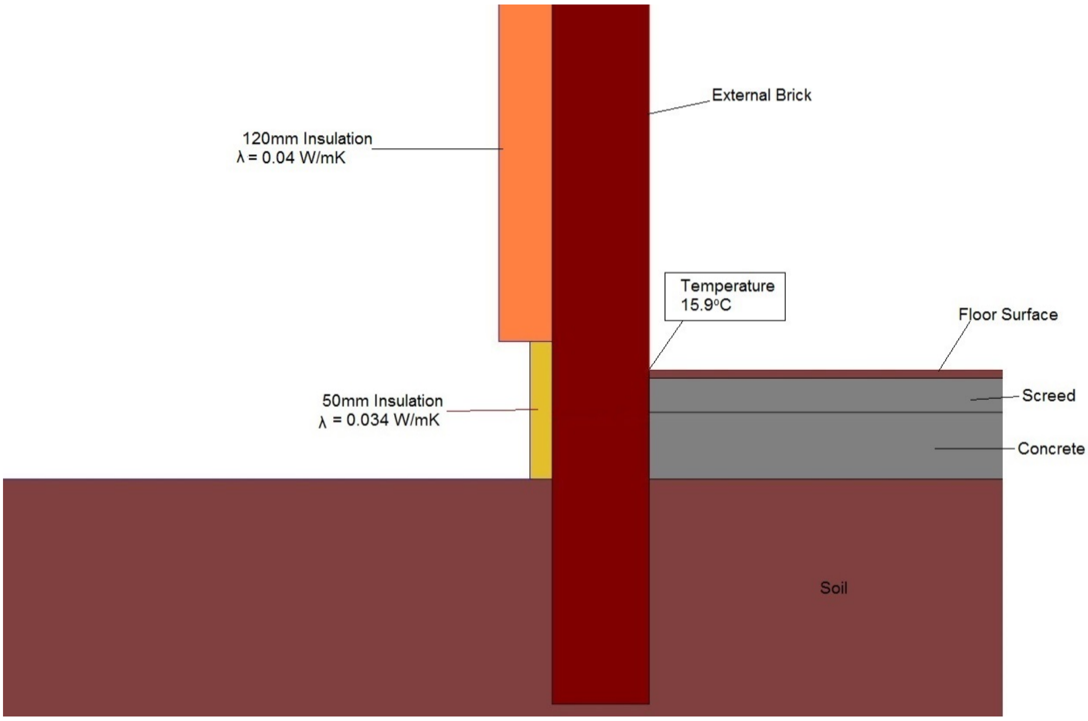


Figure 184: Junction between an uninsulated concrete ground floor and a wall insulated externally (typology R9) with below DPC insulation

- Results Analysis

Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (T_{si}) is 15.9°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.79, which indicates no risk of mould growth.

31.2.2. Build-up - Insulated ground bearing floor (typology R2) with EWI (typology R9)

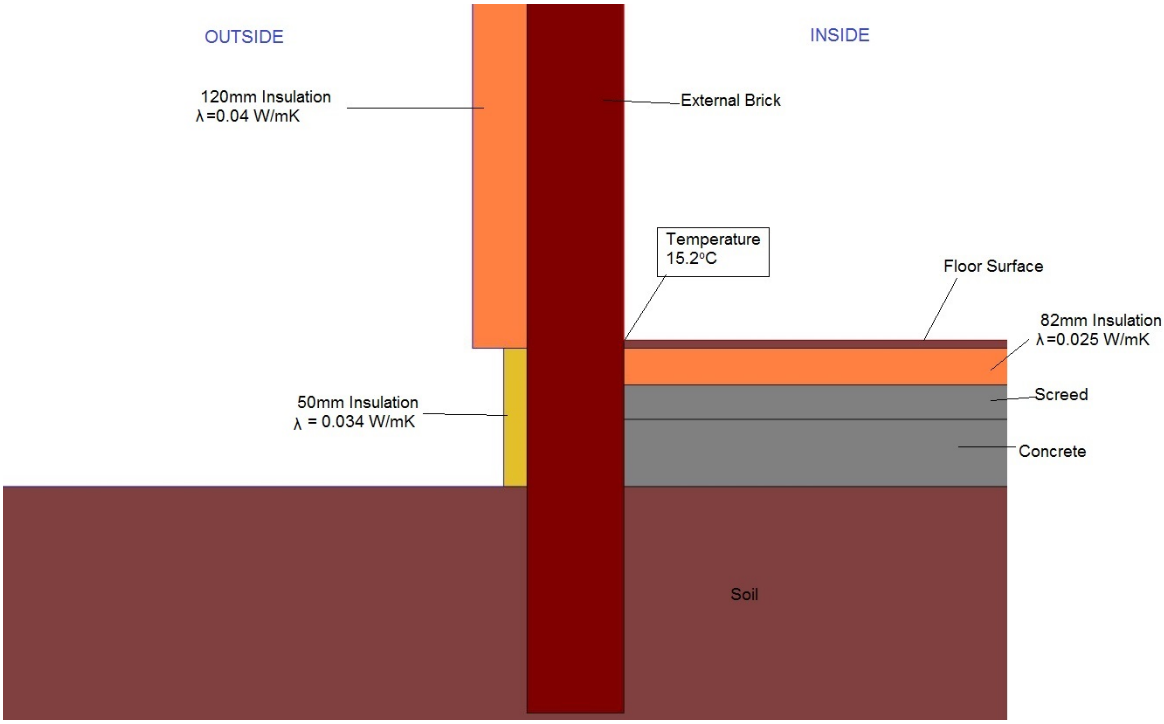


Figure 185: Junction between an insulated ground bearing floor (R2) and a wall insulated externally (R9) with below DPC insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (Tsi) is 15.2°C. With an external temperature of 0°C, the resultant fRsi is 0.76, which indicates a moderate risk of mould growth.

31.2.3. Conclusions

- The insulation below the DPC level (XPS) substantially reduces the risk.
- In this scenario insulation at floor level doesn't improve and slightly worsens the situation to a border line case.

31.3. Ground floor suspended / Wall junction - EWI and IWI

31.3.1. Build-up - Uninsulated floor with EWI (typology R9)

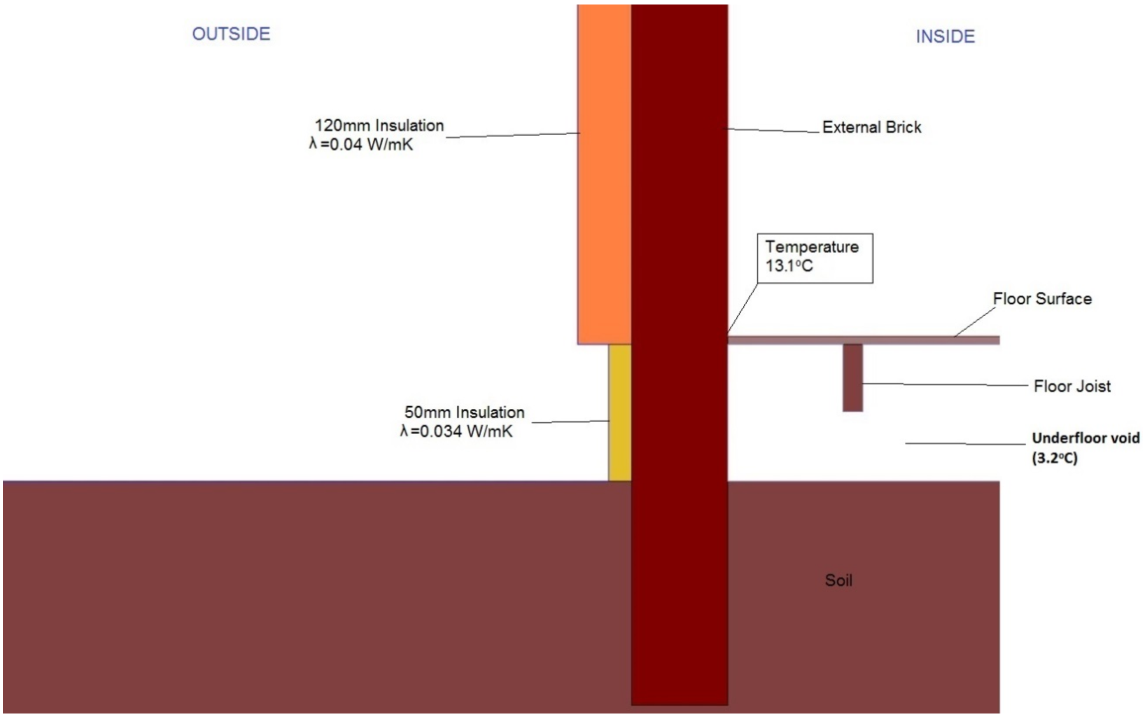


Figure 186: Junction between an uninsulated suspended ground floor and a wall with external insulation (typology R9) with below DPC insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 13.1°C at the junction corner. With an external temperature of 0°C and a temperature under floor of 3.2°C, the resultant f_{Rsi} is 0.59, which indicates a high risk of mould growth at this junction.

31.3.2. Build-up - Insulated floor (typology R1) with EWI (typology R9)

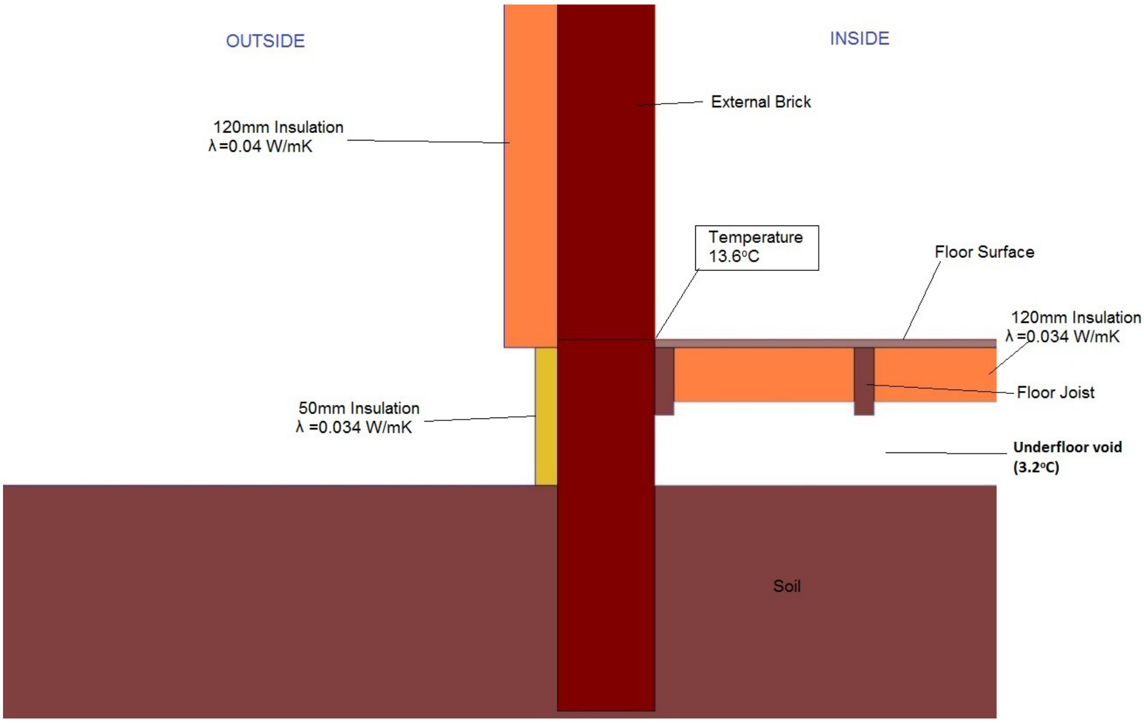


Figure 187: Junction between an insulated suspended ground floor (typology R1) and a wall with external insulation (typology R9) with edge and below DPC insulation

- Results Analysis

Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (T_{si}) is 13.6°C at the junction corner. With an external temperature of 0°C and a temperature under floor of 3.2°C, the resultant f_{Rsi} is 0.62, which indicates a high risk of mould growth at this junction.

31.3.3. Build-up - Insulated floor (typology R1) with EWI (typology R9)

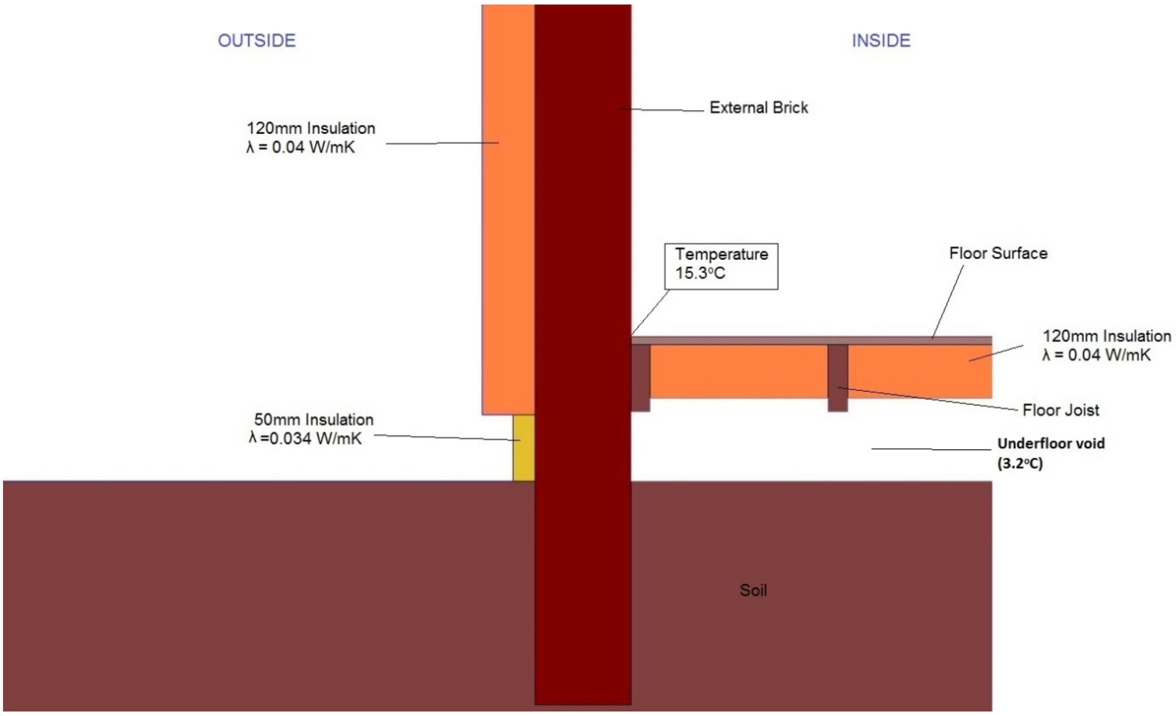


Figure 188: Junction between an insulated suspended ground floor (typology R1) and a wall with external insulation (typology R9) with below DPC insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 15.3°C at the junction corner. With an external temperature of 0°C and a temperature under floor of 3.2°C, the resultant f_{Rsi} is 0.72, which indicates some risk of mould growth at this junction.

31.3.4. Conclusions

- External perimeter insulation alone will not sufficiently reduce mould growth risk at this junction, but will reduce risk.
- Underfloor insulation should be considered.

32. Windows

32.1. Window head - cill - jamb / solid wall - EWI and IWI

32.1.1. Build-up - Window head - cill - jamb / solid wall with EWI (typology R9)

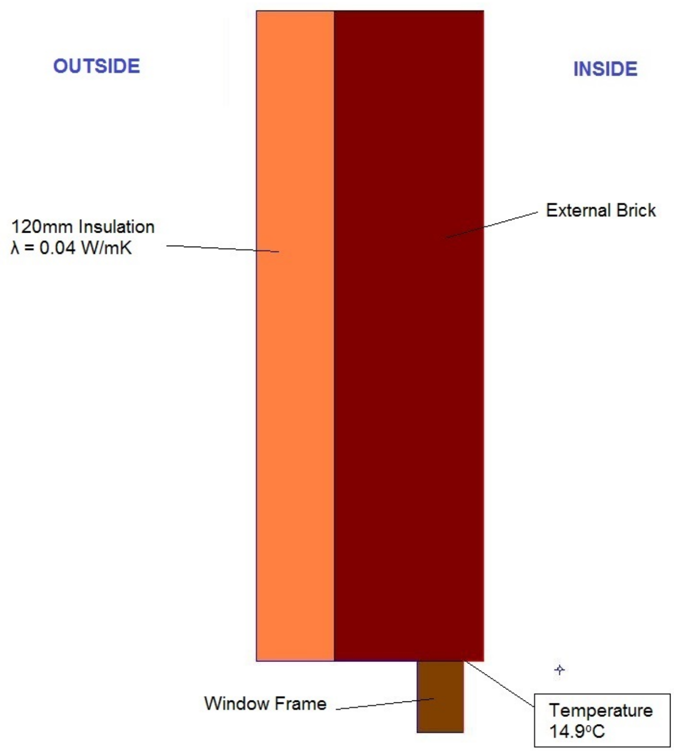


Figure 189: Junction between a window head-cill-jamb and a solid wall (typology R9) with no junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (Tsi) is 14.9°C. With an external temperature of 0°C, the resultant fRsi is 0.75, which indicates some risk of mould growth. This result applies to window heads, cills and jambs, which have been modelled in the same way for ease of reference.

32.1.2. Build-up - Window head - cill - jamb / solid wall with EWI (typology R9)

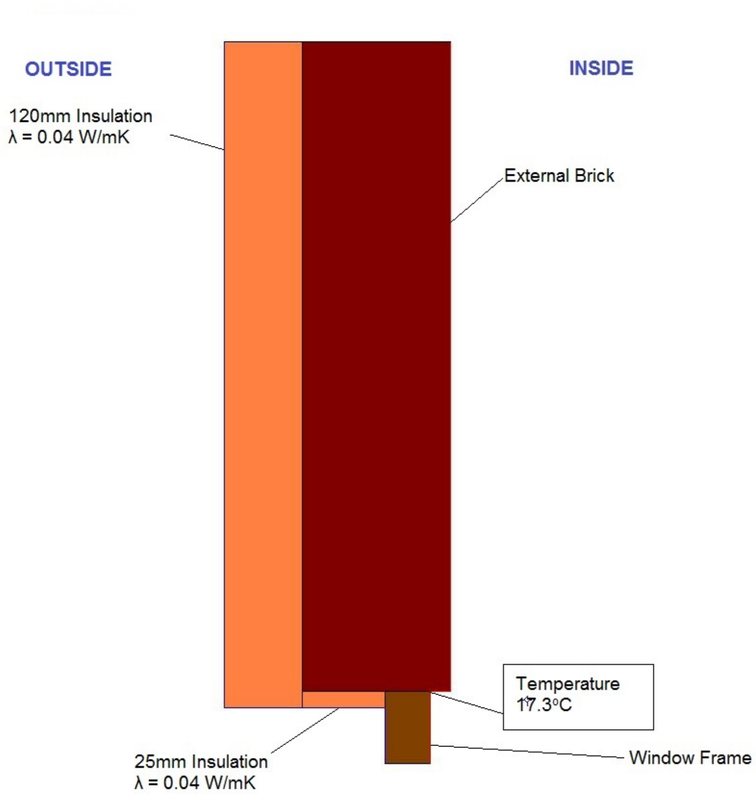


Figure 190: Junction between a window head-cill-jamb and a solid wall (typology R9) with reveal insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 17.3°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.87, which indicates no risk of mould growth at this junction. This result applies to window heads, cills and jambs, which have been modelled in the same way for ease of reference.

32.1.3. Build-up - Window head - cill - jamb / solid wall with IWI (typology R8)

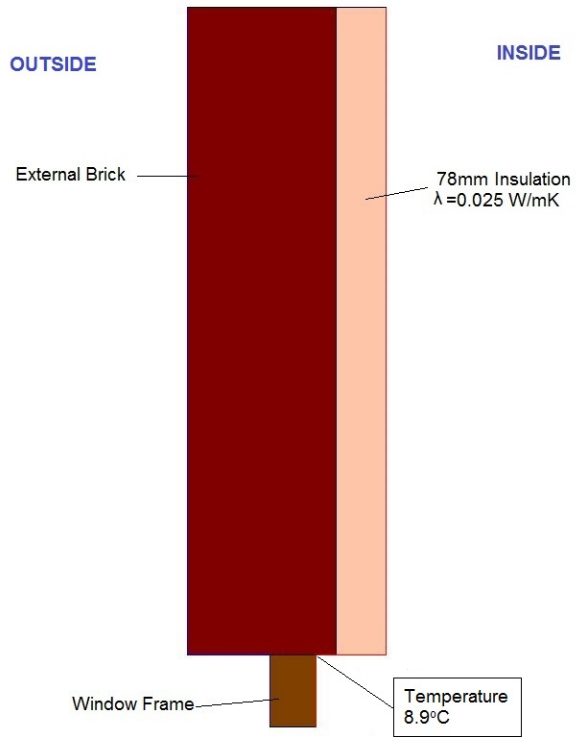


Figure 191: Junction between a window head-cill-jamb and a solid wall (typology R8) with no junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (Tsi) is 8.9°C. With an external temperature of 0°C, the resultant fRsi is 0.45, which indicates a very high risk of mould growth at this junction.

32.1.4. Build-up - Window head - cill - jamb / solid wall with IWI (typology R8)

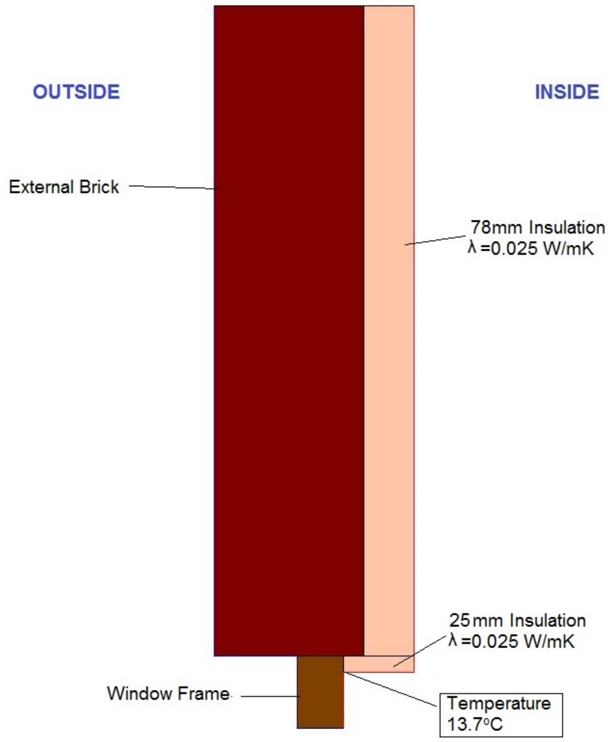


Figure 192: Junction between a window head-cill-jamb and a solid wall (typology R8) with reveals insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 13.7°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.69, which indicates a risk of mould growth at this junction.

32.1.5. Conclusions

- Only the EWI with return insulation case can be considered a robust solution to avoiding mould growth risk at retrofit wall / window junctions.

33. Upper Floors

33.1. First floor edge with solid wall IWI

33.1.1. Build-up - Uninsulated floor / solid wall with IWI (typology R8)

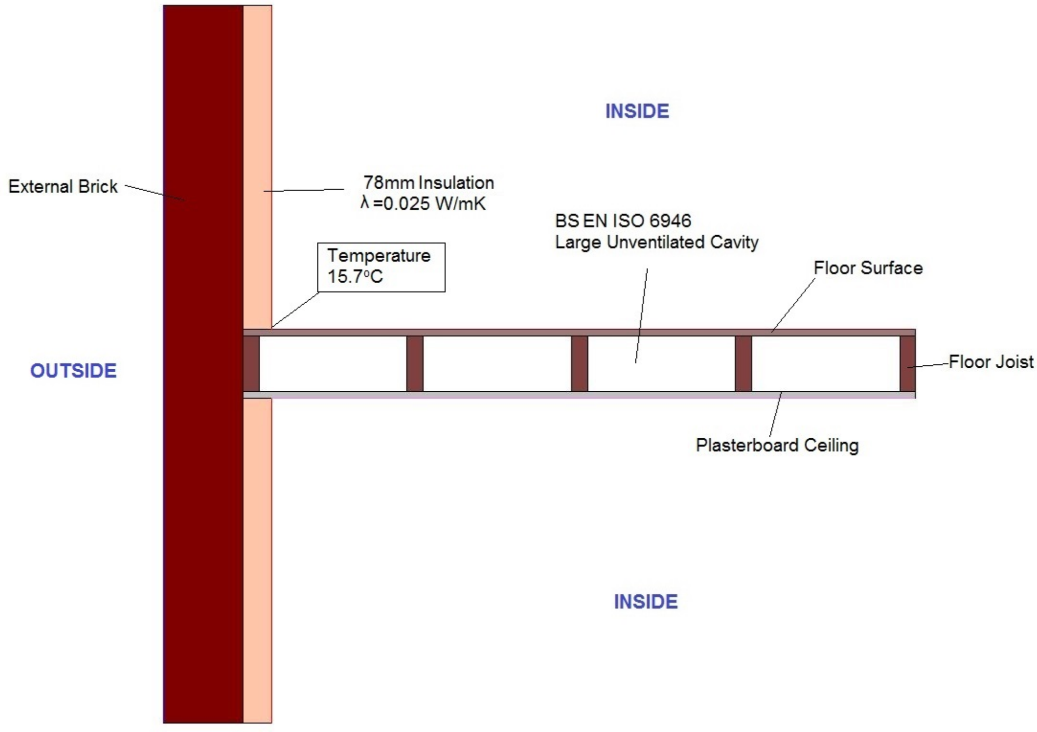


Figure 193: Junction between an upper uninsulated floor and a solid wall (typology R8) with no junction insulation

- Results Analysis

Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (T_{si}) is 15.7°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.79, which indicates a low risk of mould growth.

33.1.2. Build-up - Insulation at the perimeter / solid wall with IWI (typology R8)

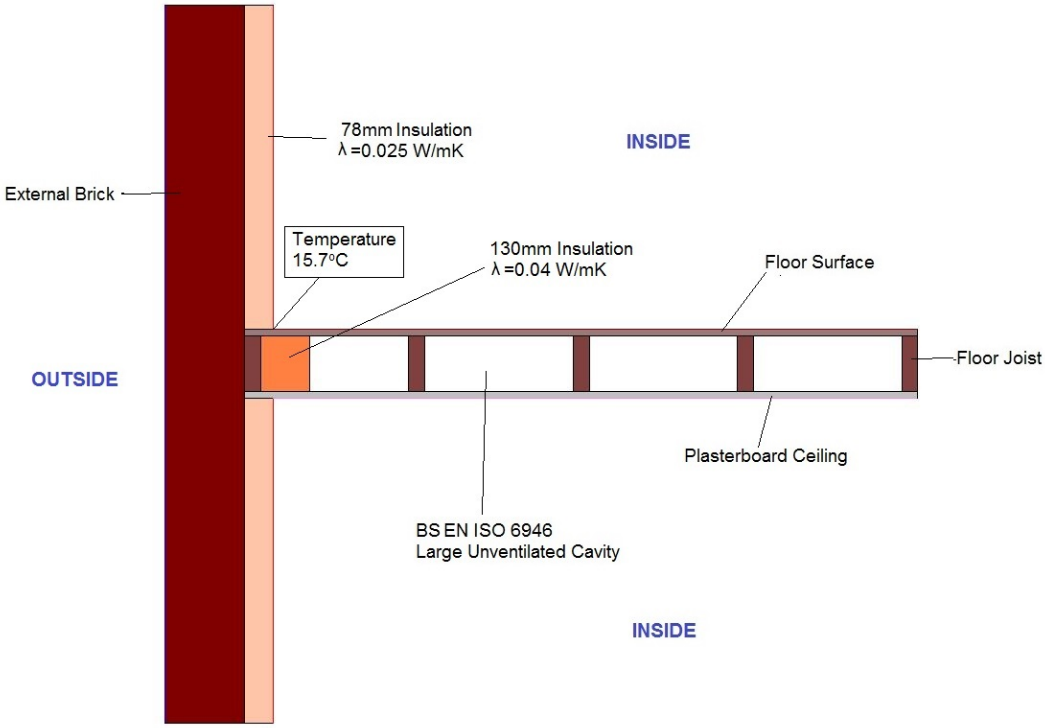


Figure 194: Junction between an upper floor with insulation at the perimeter and a solid wall (typology R8)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is unchanged at 15.7°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.79, which indicates a low risk of mould growth at this junction.

33.1.3. Build-up - Uninsulated floor / solid wall with IWI (typology R8)

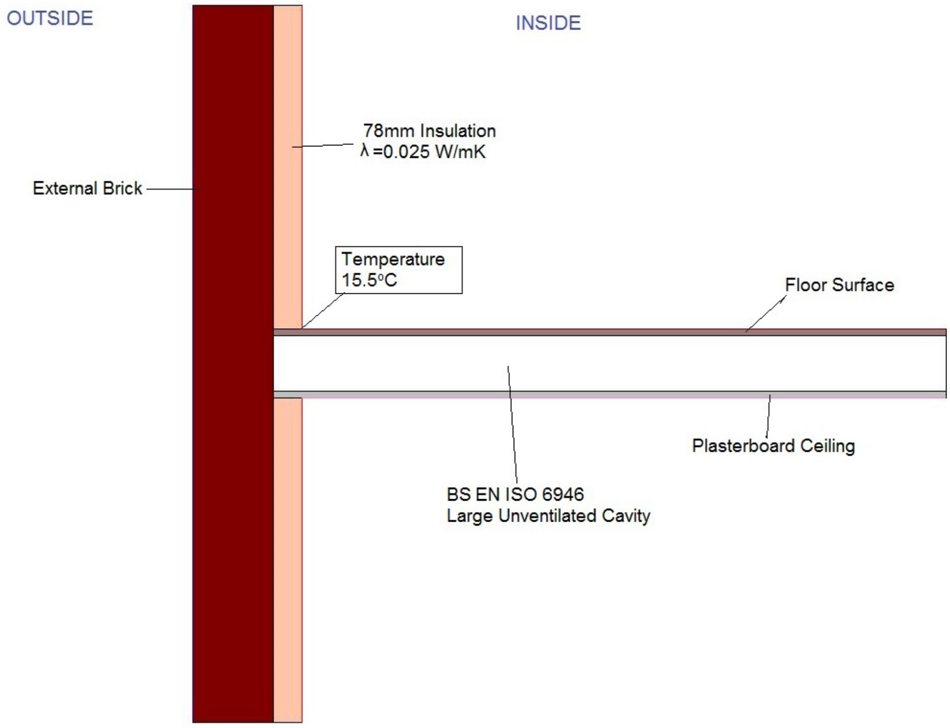


Figure 195: Junction between an upper uninsulated floor and a solid wall (typology R8) with no junction insulation (cross section along the joists)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 15.5°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.78, which indicates a low risk of mould growth at this junction.

33.1.4. Build-up - Insulated floor / solid wall with IWI (typology R8)

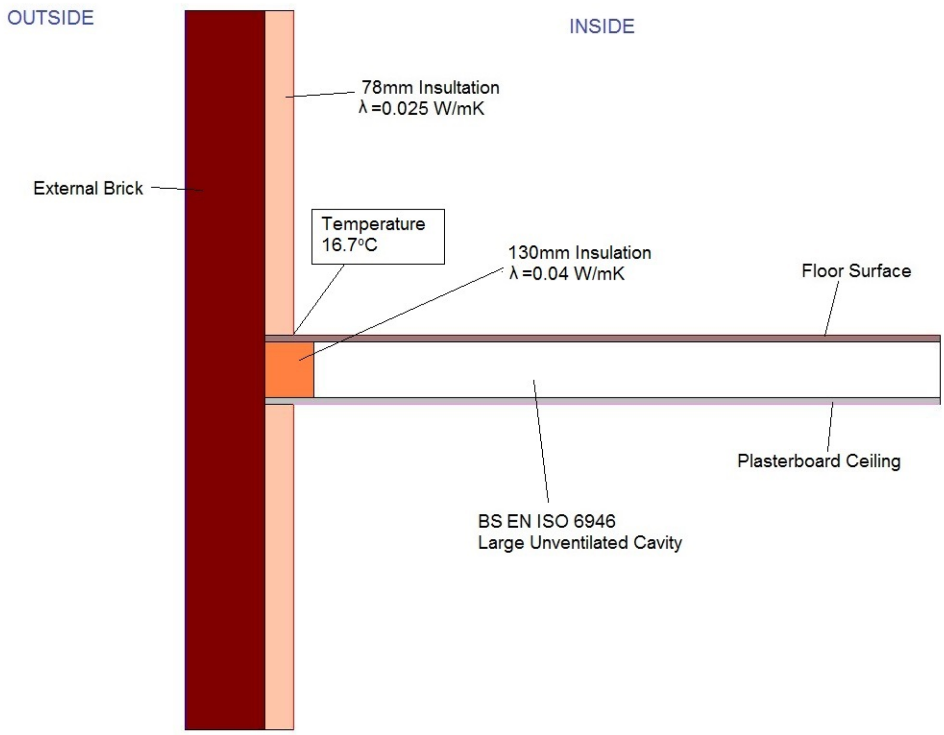


Figure 196: Junction between an upper floor with insulation at the perimeter and a solid wall (typology R8) - (cross section along the joists)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 16.7°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.84, which indicates a low risk of mould growth at this junction.

33.1.5. Conclusions

- Installing perimeter insulation at floor joists reduces risk of mould growth only when not commensurate with floor joists.

33.2. Stair String with solid wall IWI (typology R8)

33.2.1. Build-up - uninsulated junction

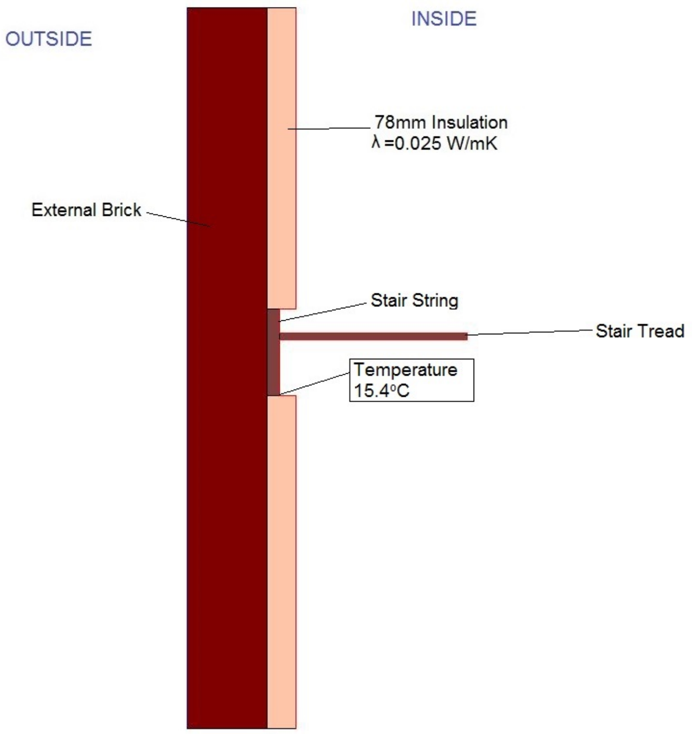


Figure 197: Junction between the stairs and a solid wall (typology R8) with no junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (Tsi) is 15.4°C. With an external temperature of 0°C, the resultant fRsi is 0.77, which indicates a low risk of mould growth.

33.2.2. Build-up - insulated uninsulated junction

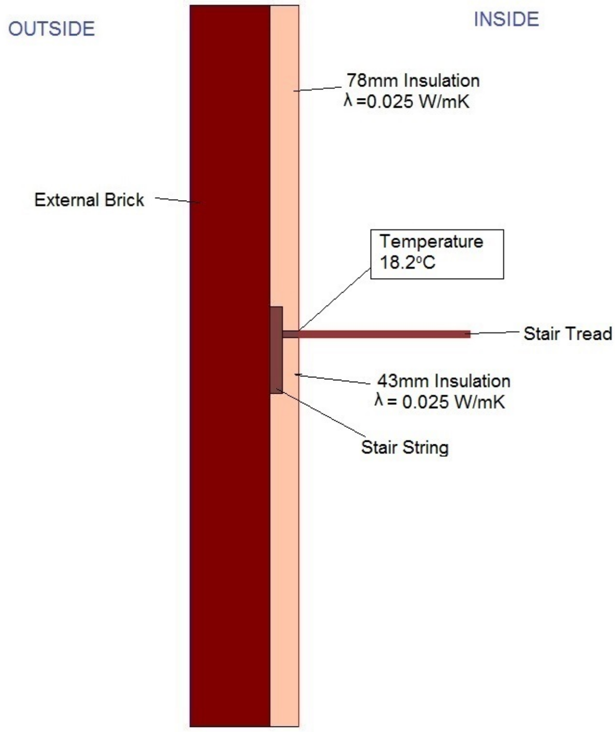


Figure 198: Junction between the stairs and a solid wall (typology R8) with 43mm junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 18.2°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.91, which indicates a very low risk of mould growth at this junction.

33.2.3. Build-up - thin junction insulation

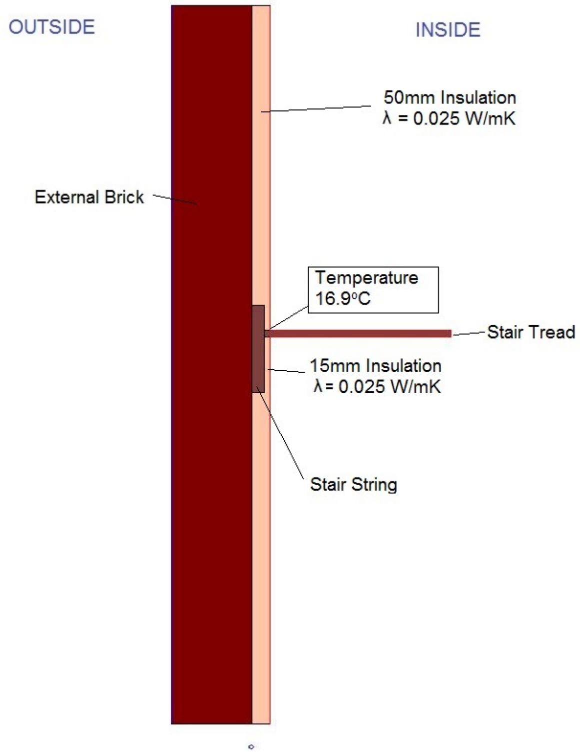


Figure 199: Junction between the stairs and a solid wall (typology R8) with 15mm junction insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 16.9°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.85, which indicates a low risk of mould growth at this junction.

33.2.4. Build-up - Asymmetric junction insulation

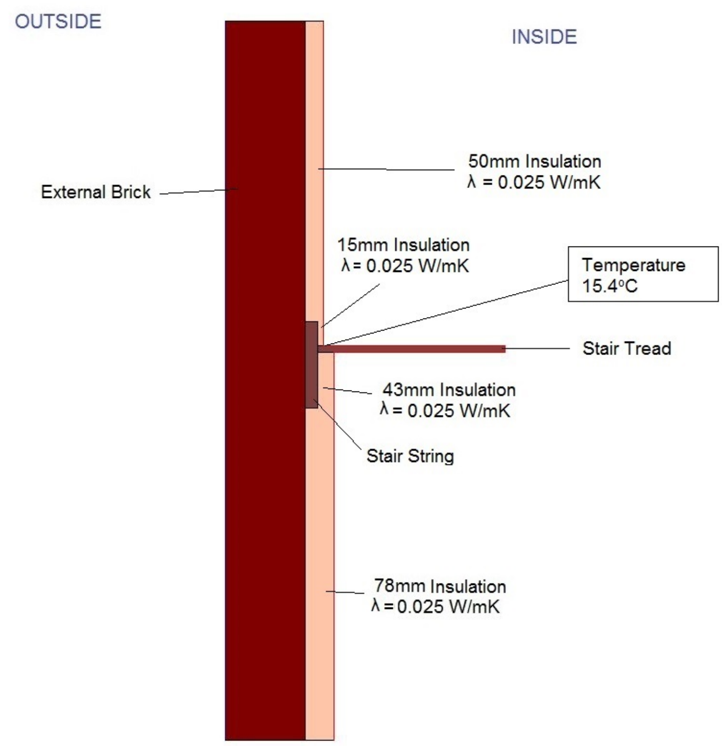


Figure 200: Junction between the stairs and a solid wall (typology R8) with asymmetric insulation

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 15.4°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.77, which indicates a low risk of mould growth at this junction, although higher than the previous scenario.

33.2.5. Conclusions

- Installing insulation over the stair string reduces risk of mould growth - equal amounts must be applied above and below stair tread to benefit.

34. Exposed Floors

34.1. Exposed Floor - IWI (typology R8)

34.1.1. Build-up - (IWI no floor insulation)

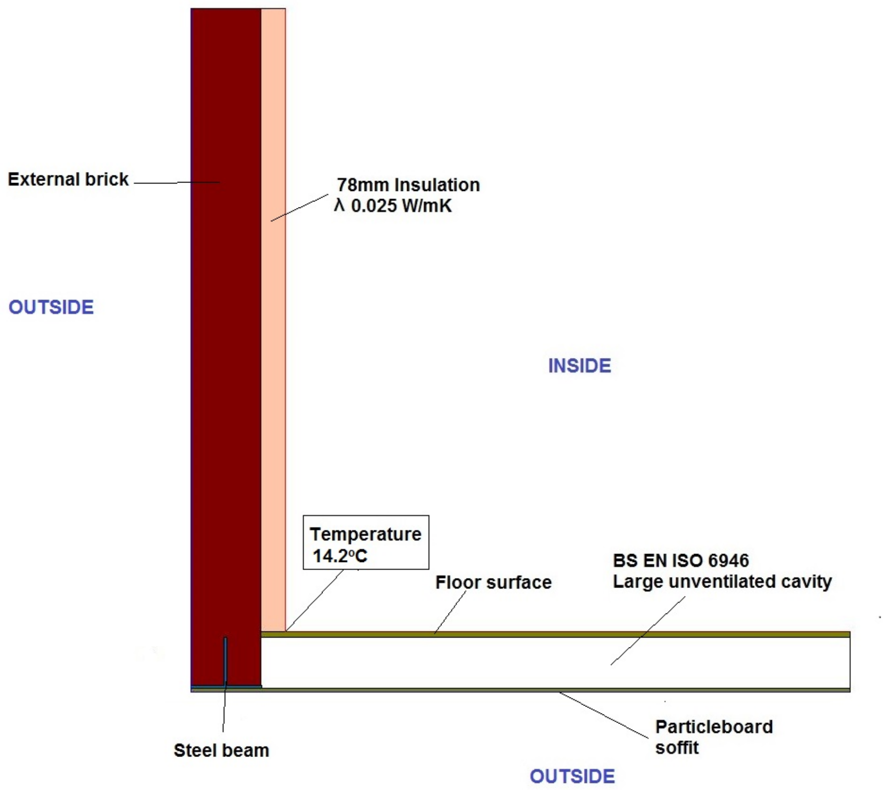


Figure 201: Junction between an exposed uninsulated floor and a solid wall (typology R8)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 14.2°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.71, which indicates a risk of mould growth

34.1.2. Build-up - (IWI with floor insulation between joists)

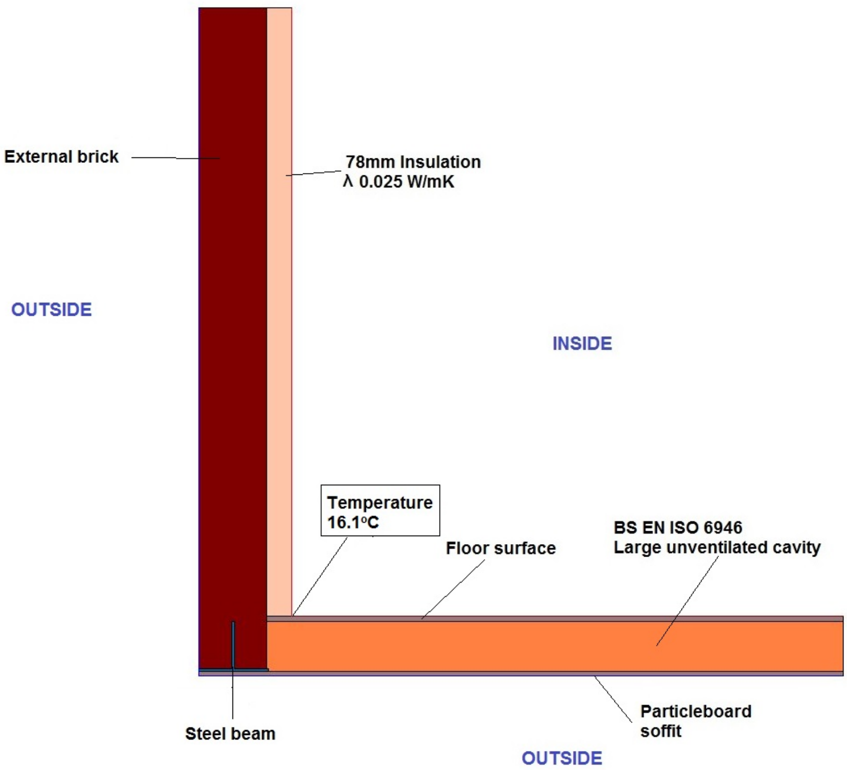


Figure 202: Junction between an exposed insulated floor and a solid wall (typology R8)

- Results Analysis

Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (Tsi) is 16.1°C. With an external temperature of 0°C, the resultant fRsi is 0.81, which indicates a low risk of mould growth at this junction

34.2. Exposed Floor - EWI (typology R9)

34.2.1. Build-up - (EWI no floor insulation)

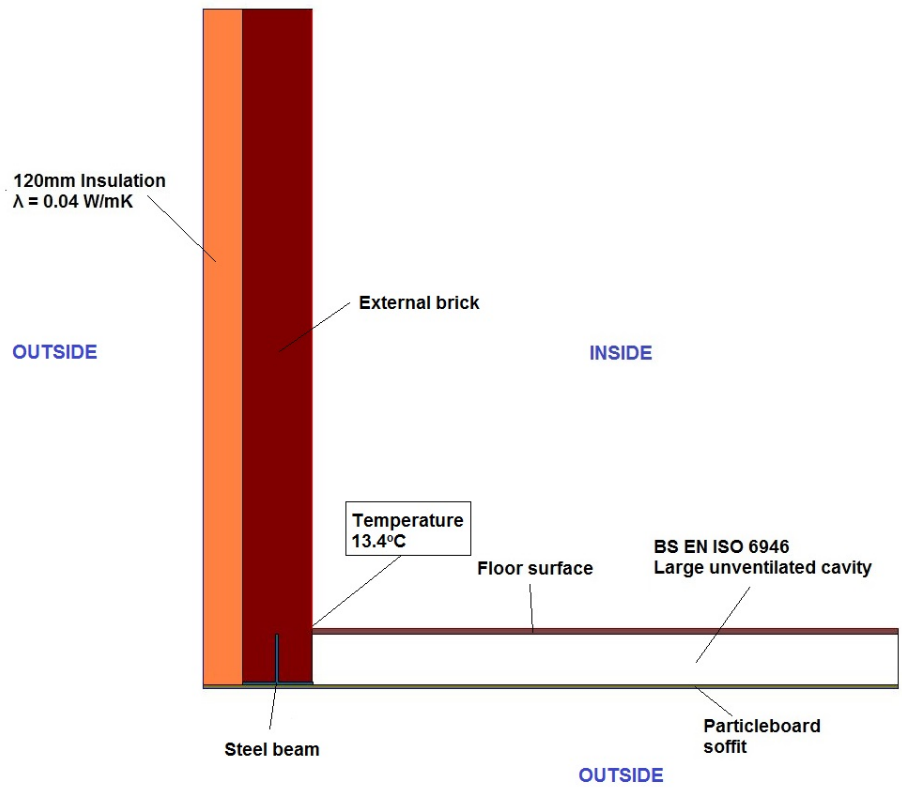


Figure 203: Junction between an upper uninsulated floor and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 13.4°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.67, which indicates a high risk of mould growth at this junction.

34.2.2. Build-up - (EWI with floor insulation between joists)

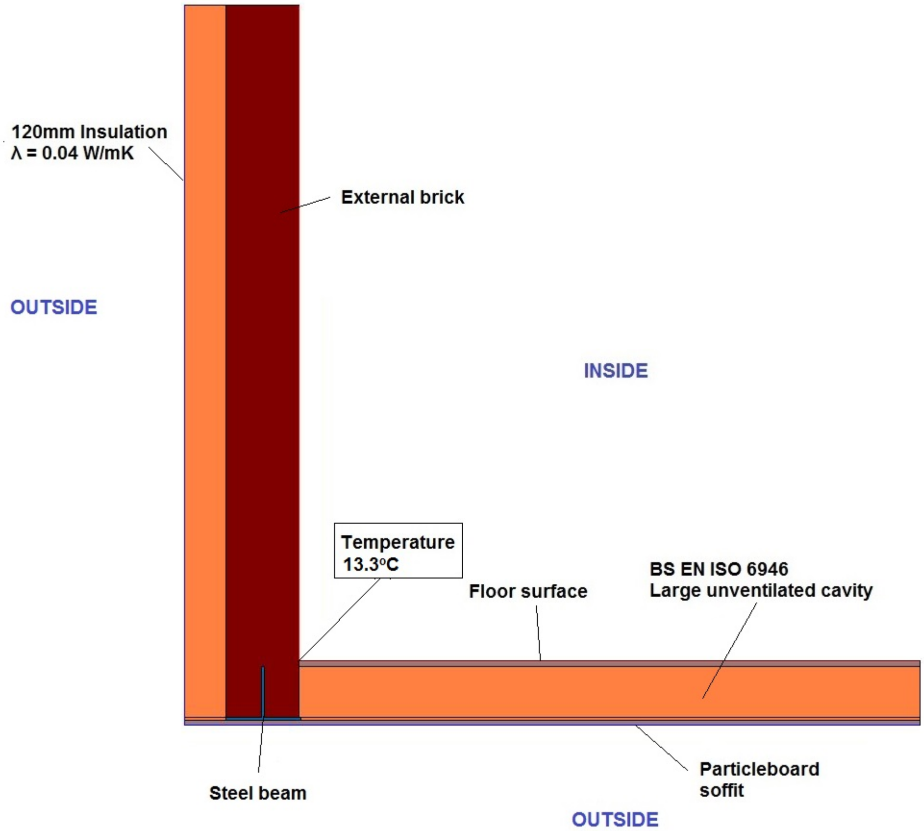


Figure 204: Junction between an upper insulated floor and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 13.3°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.67, which indicates a high risk of mould growth at this junction.

34.2.3. Conclusions

- Only the IWI with floor insulation between joists case can be considered a robust solution to avoiding mould growth risk at retrofit wall / exposed floor junctions.

34.3. Exposed Floor (Inverted) - IWI (typology R8)

34.3.1. Build-up - (IWI no floor insulation)

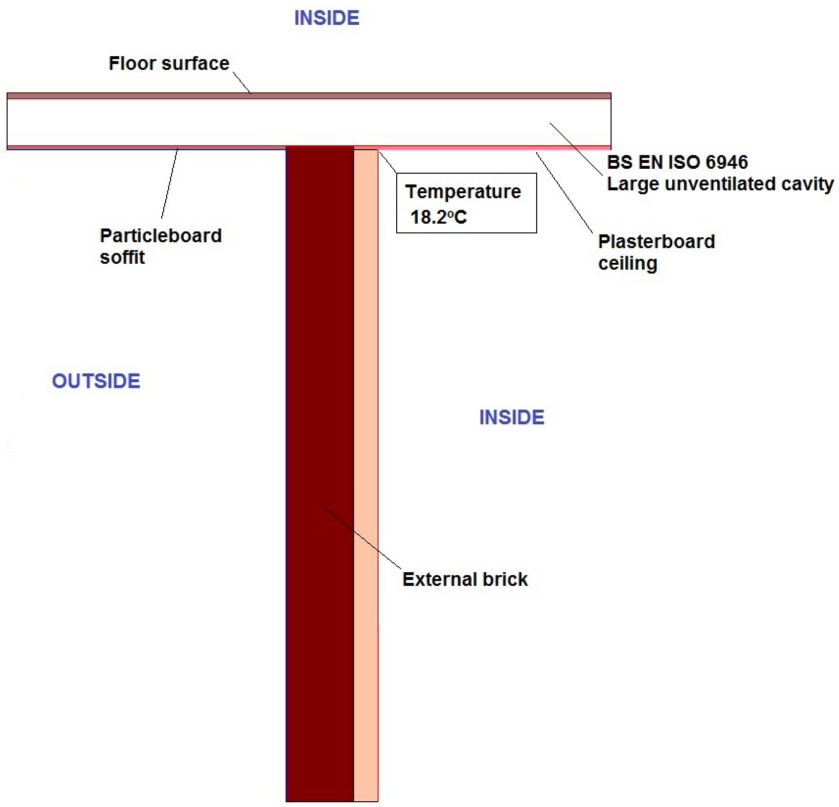


Figure 205: Junction between an un-insulated exposed floor (inverted) and a solid wall (typology R8)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (Tsi) is 18.2°C. With an external temperature of 0°C, the resultant fRsi is 0.91, which indicates a very low risk of mould growth at this junction.

34.3.2. Build-up - (IWI with floor insulation between joists)

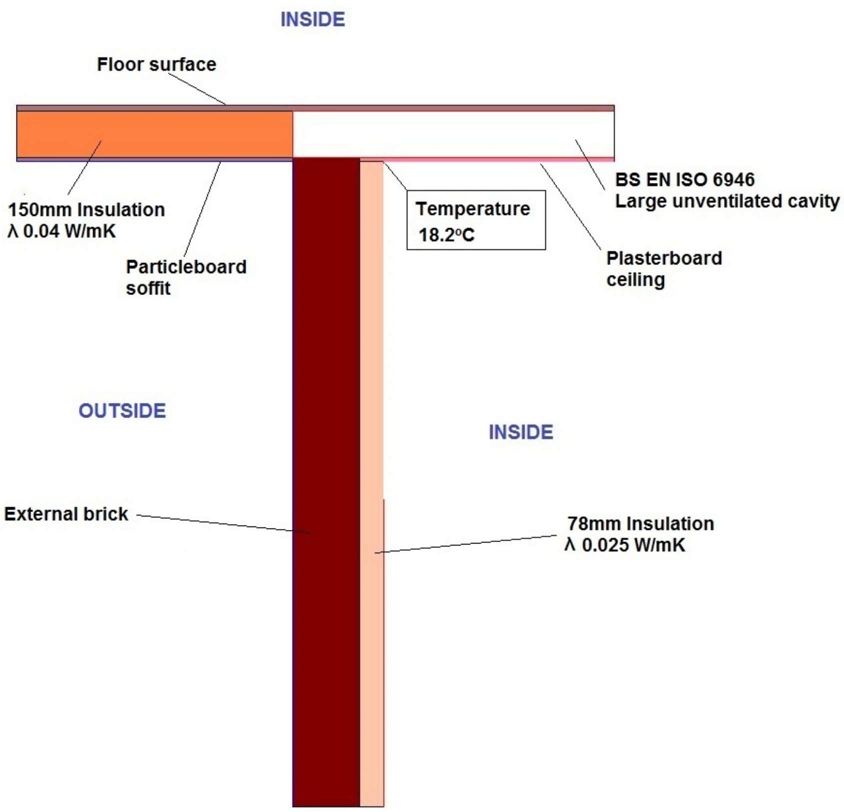


Figure 206: Junction between an insulated exposed floor (inverted) and a solid wall (typology R8)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is unchanged at 18.2°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.91, which indicates a very low risk of mould growth at this junction.

34.3.3. Build-up - (IWI with external floor insulation below)

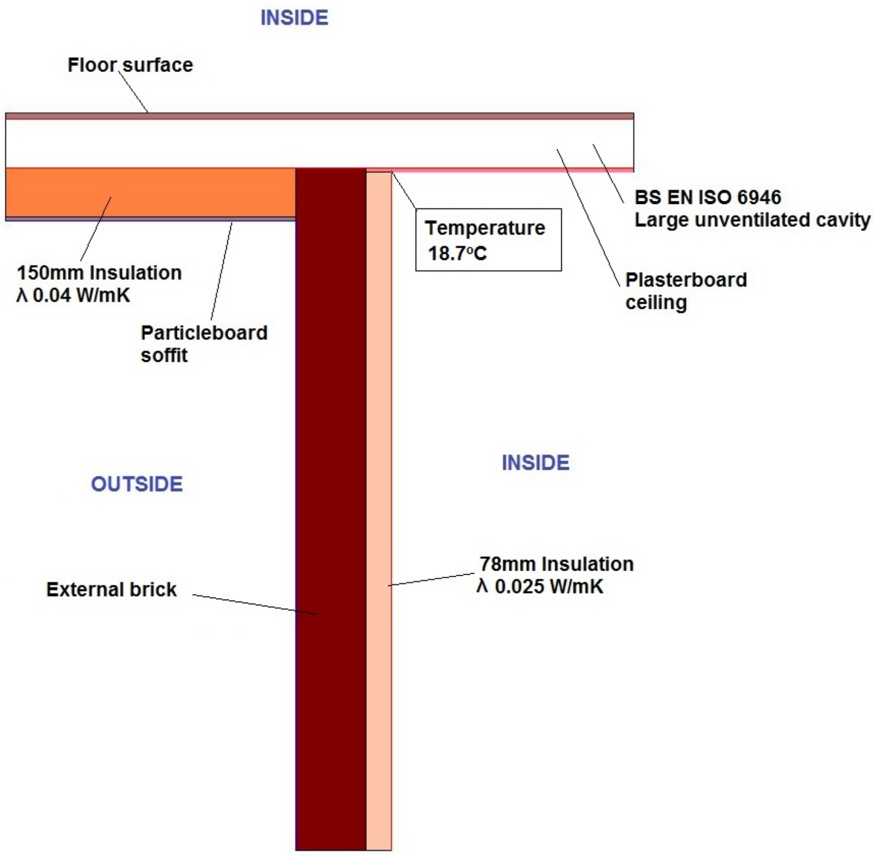


Figure 207: Junction between an insulated exposed floor (inverted) and a solid wall (typology R8)

- Results Analysis

Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (T_{si}) is 18.7°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.94, which indicates a very low risk of mould growth at this junction.

34.3.4. Conclusions

- Can be considered a safe junction with IWI.
- Installing floor insulation is beneficial to $f_{Rsi.}$ With increased value where external floor insulation is installed.

34.4. Exposed Floor (Inverted) - EWI (typology R9)

34.4.1. Build-up - (EWI with no floor insulation)

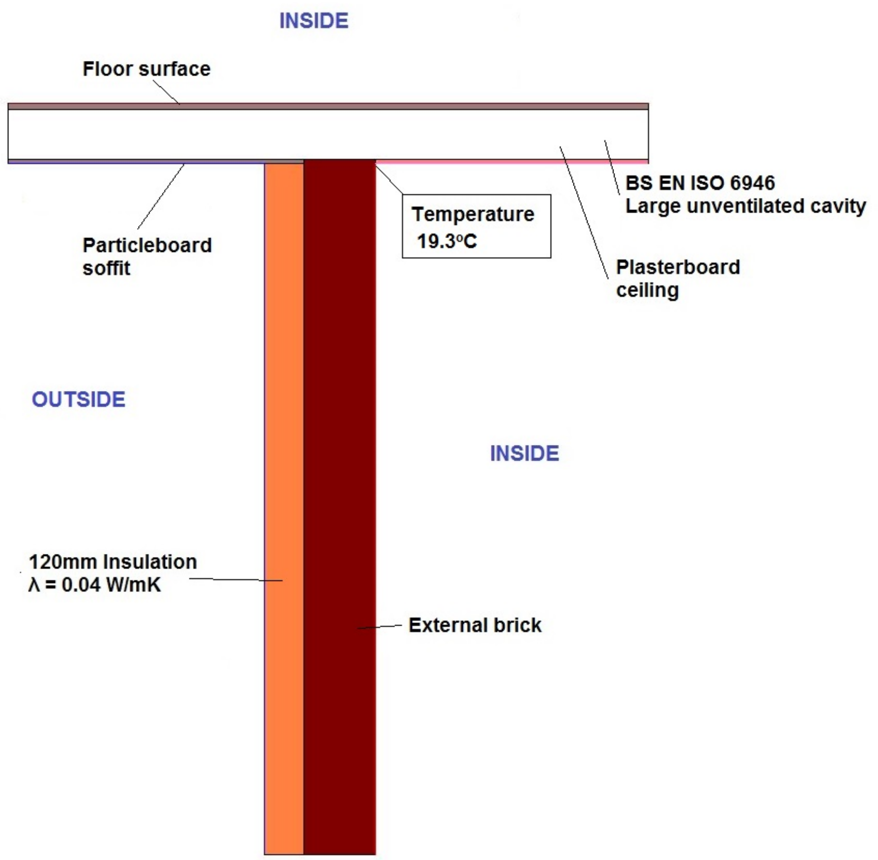


Figure 208: Junction between an un-insulated exposed floor (inverted) and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 19.3°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.97, which indicates a very low risk of mould growth at this junction.

34.4.2. Build-up - (EWI with floor insulation between joists)

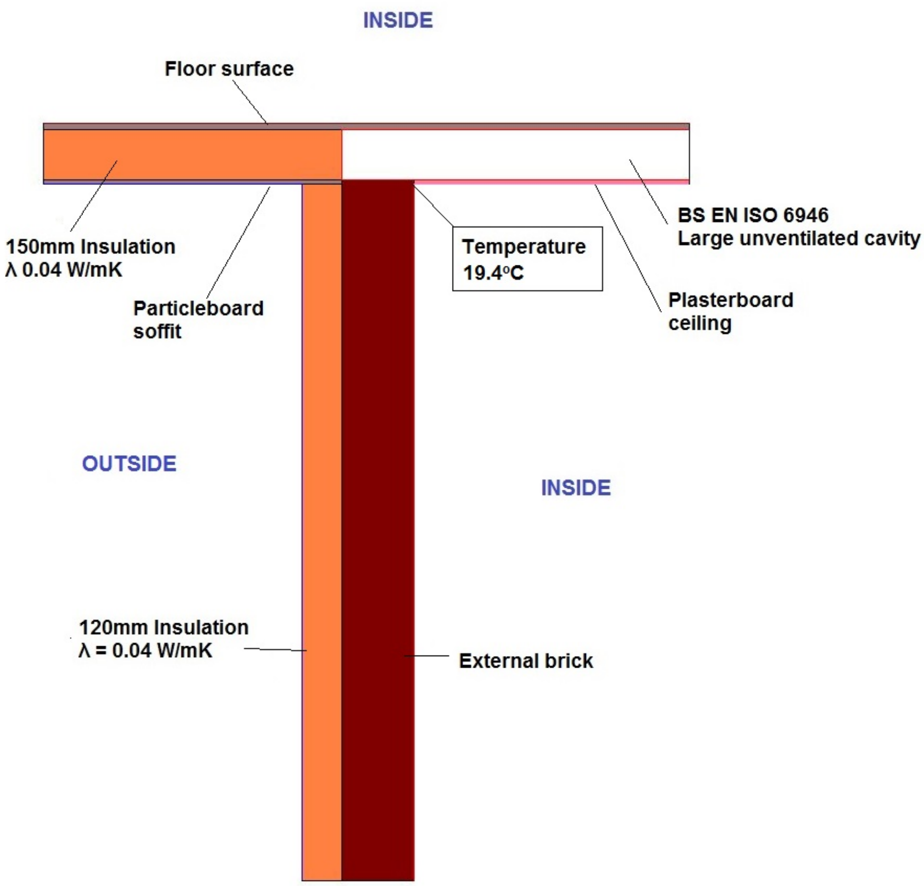


Figure 209: Junction between an insulated exposed floor (inverted) and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 19.4°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.97, which indicates a very low risk of mould growth at this junction.

34.4.3. Build-up - (EWI with external floor insulation below)

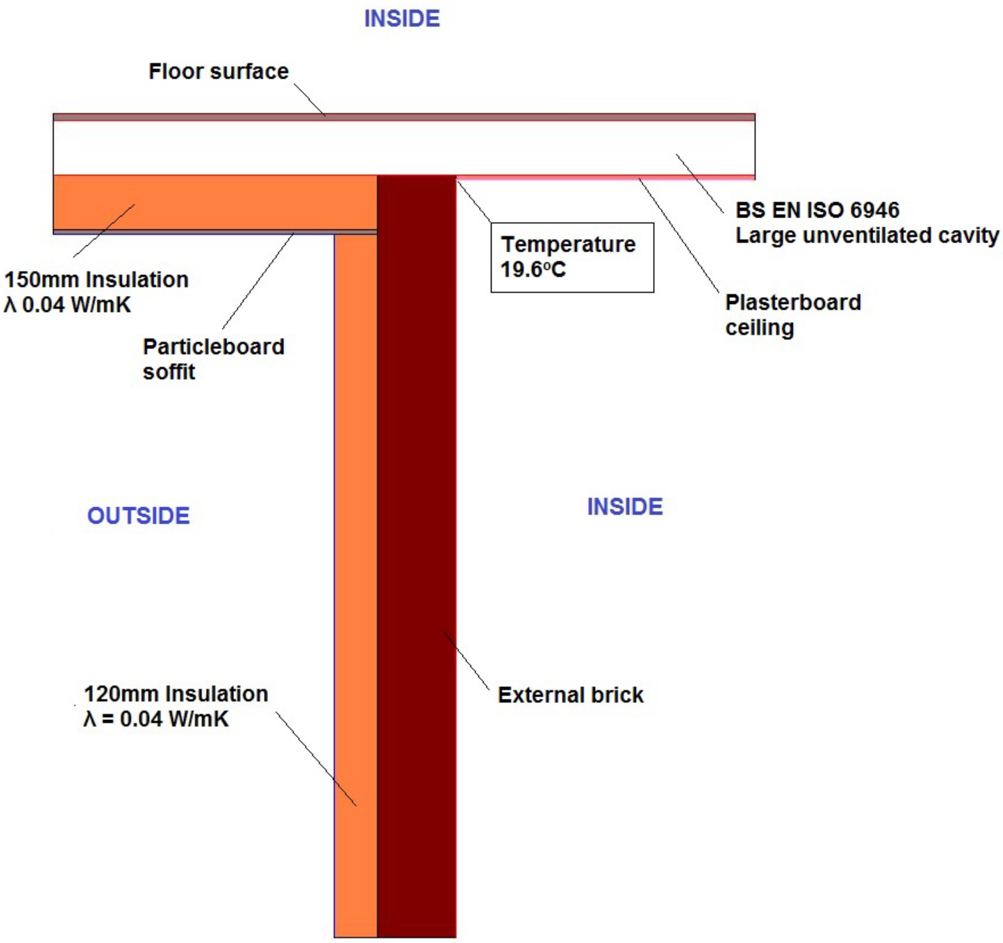


Figure 210: Junction between an insulated exposed floor (inverted) and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 19.6°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.98, which indicates a very low risk of mould growth at this junction.

34.4.4. Conclusions

- Can be considered a safe junction with EWI
- Installing floor insulation is beneficial to $f_{Rsi.}$ With increased value where external floor insulation is installed.
- Combination of EWI and external floor insulation is the most robust against mould growth risk.

34.5. Balcony or walkway - Support penetrates wall - IWI (typology R8)

34.5.1. Build-up - (IWI)

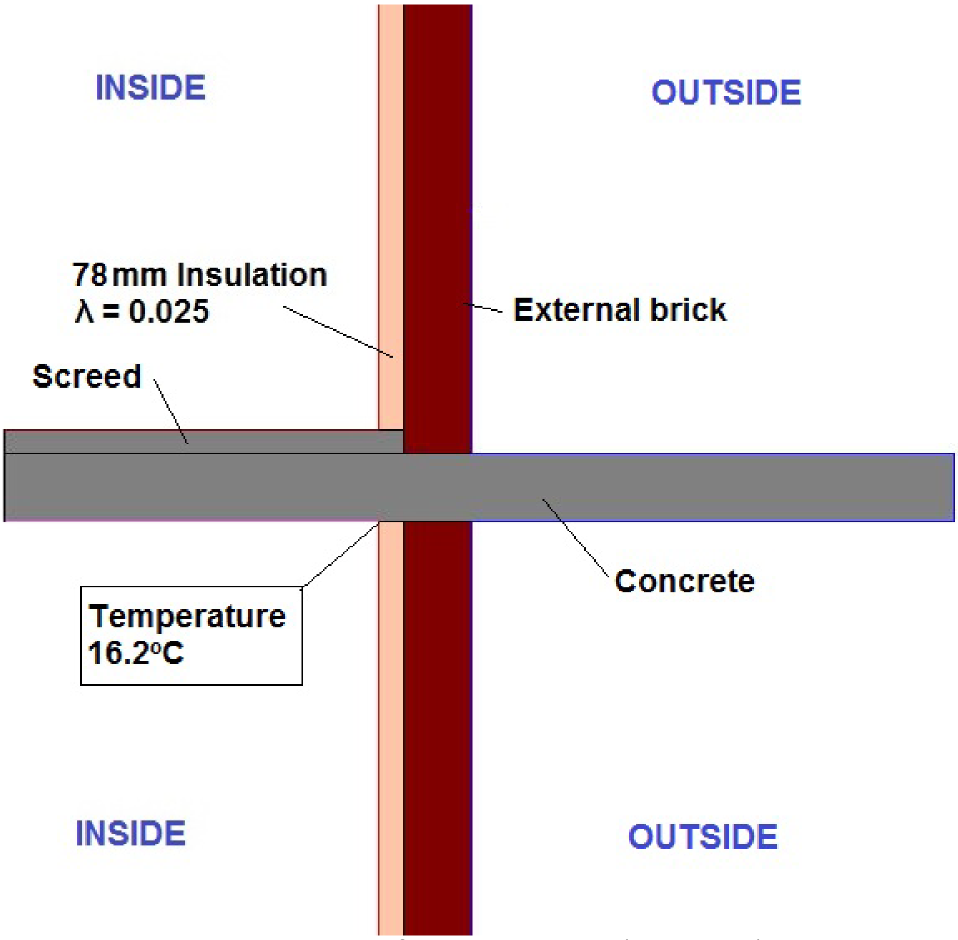


Figure 211: Junction between an upper insulated floor and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 16.2°C With an external temperature of 0°C, the resultant f_{Rsi} is 0.81, which indicates a low risk of mould growth.

34.5.2. Conclusions

- Where a fully cantilevered balcony or walkway penetrates the wall, installation of IWI will have a low risk of surface mould growth, in particular at the ceiling junction of a lower flat.

34.6. Balcony or walkway - Support penetrates wall - EWI (typology R9)

34.6.1. Build-up - (EWI)

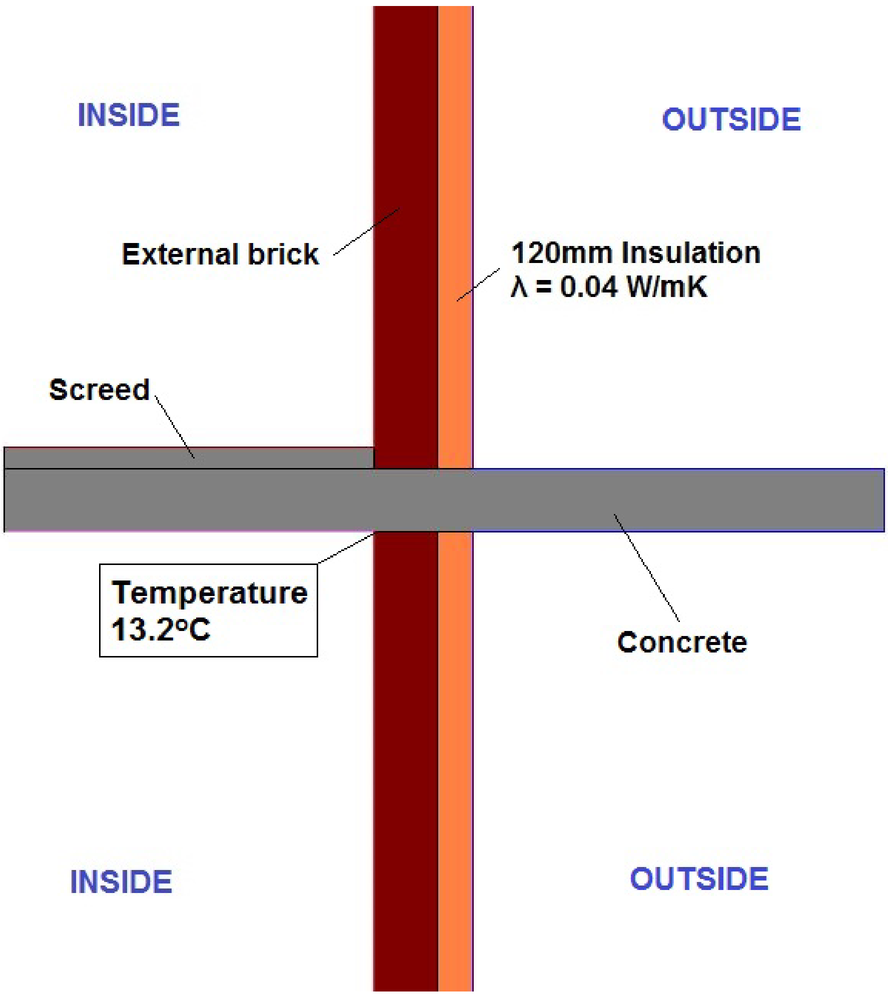


Figure 212: Junction between an upper insulated floor and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 13.2°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.67, which indicates a high risk of mould growth at this junction.

34.6.2. Conclusions

- Where a fully cantilevered balcony or walkway penetrates the wall, installation of EWI will have a high risk of surface mould growth, in either upper or lower flat.

35. Eaves

35.1. Cold roof (insulation at ceiling level) - Wall EWI (Typology R9)

35.1.1. Build-up - (EWI no wall plate insulation)

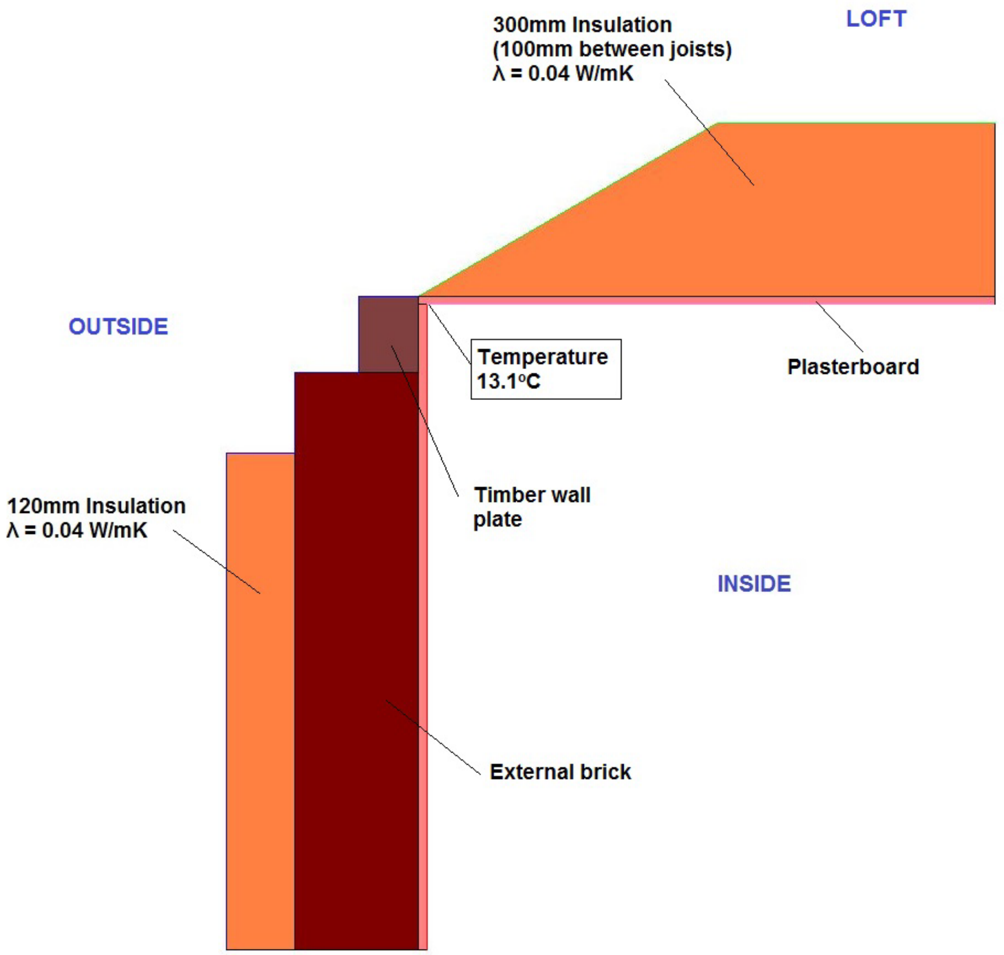


Figure 213: Junction between an insulated cold roof and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 13.1°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.66, which indicates a high risk of mould growth.

35.1.2. Build-up - (EWI with wall plate insulation)

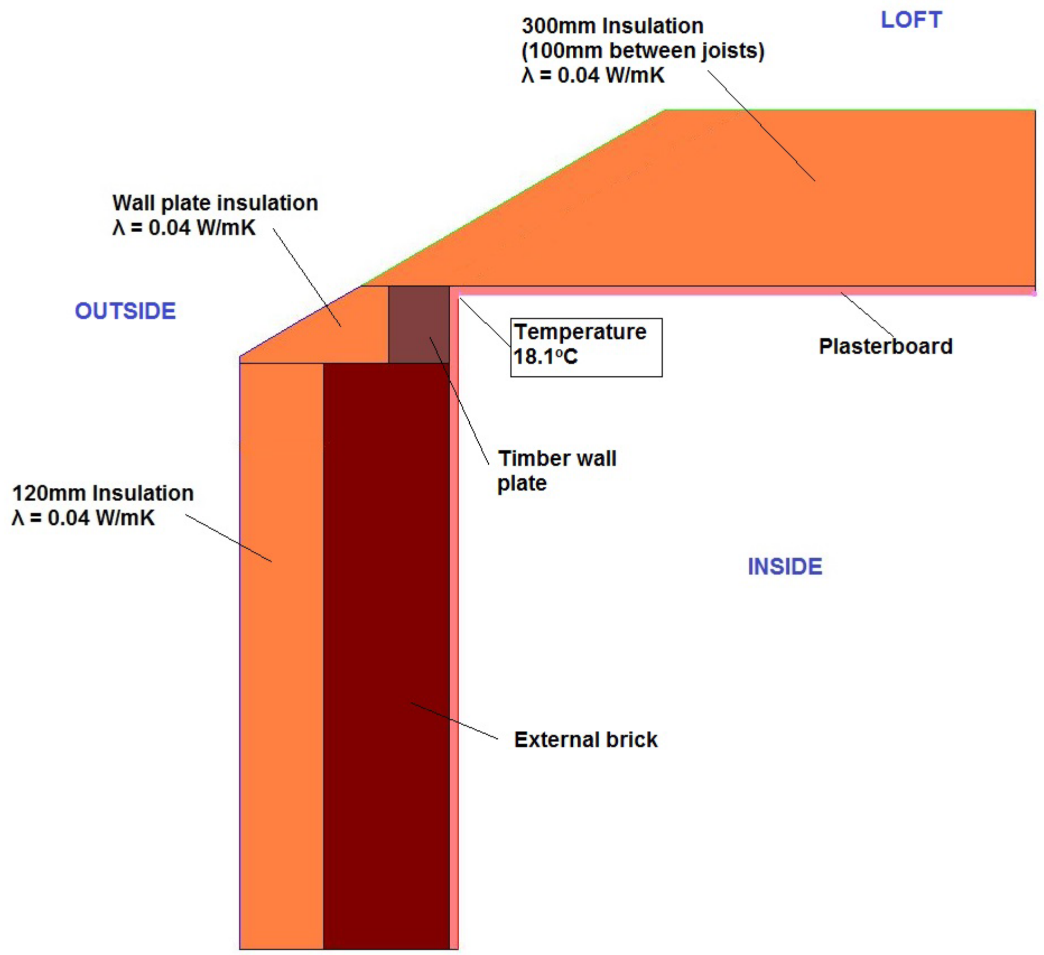


Figure 214: Junction between an insulated cold roof and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 18.1°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.91, which indicates a very low risk of mould growth at this junction.

35.1.3. Conclusions

- Installing insulation around the eaves (without restricting loft ventilation) can eliminate a risk of mould growth when both loft insulation and EWI are installed.

35.2. Warm roof sloping ceiling - Wall IWI / EWI

35.2.1. Build-up - (IWI and loft insulation with no sloping ceiling insulation)

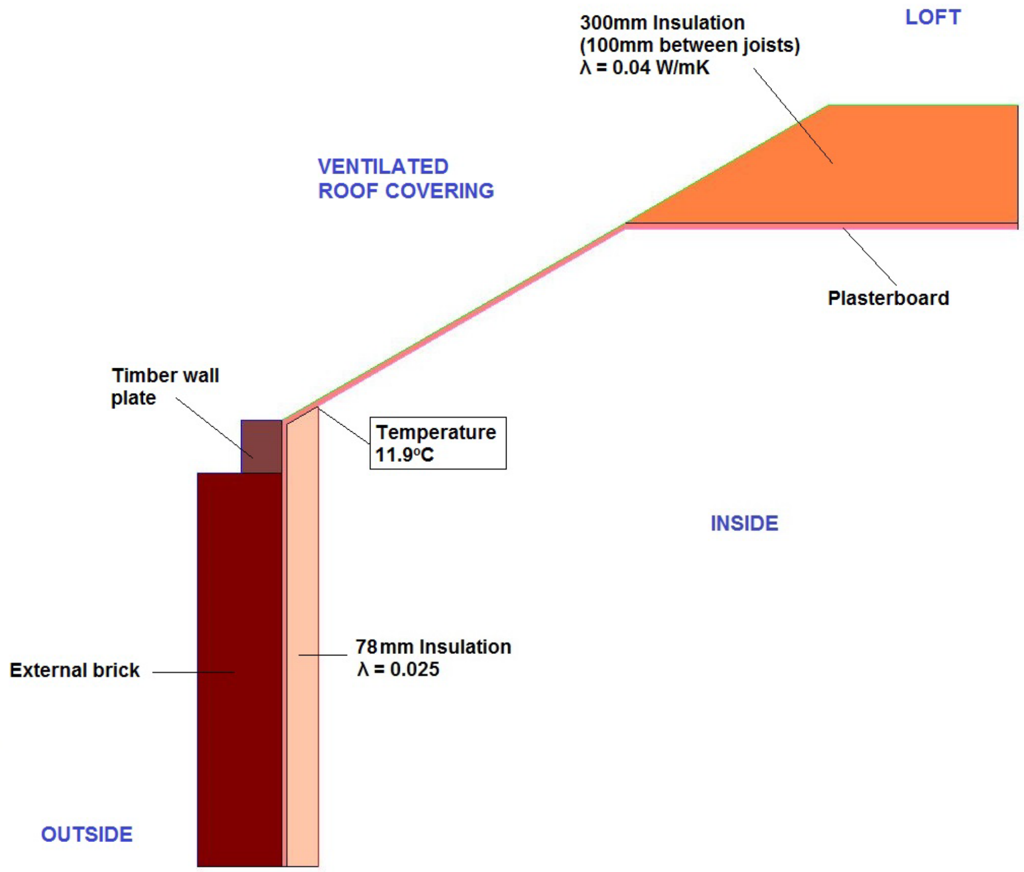


Figure 215: Junction between an insulated cold roof, an uninsulated warm (sloping ceiling) roof, and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 11.9°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.60, which indicates a high risk of mould growth.

35.2.2. Build-up - (IWI and loft insulation with sloping ceiling insulation between rafters)

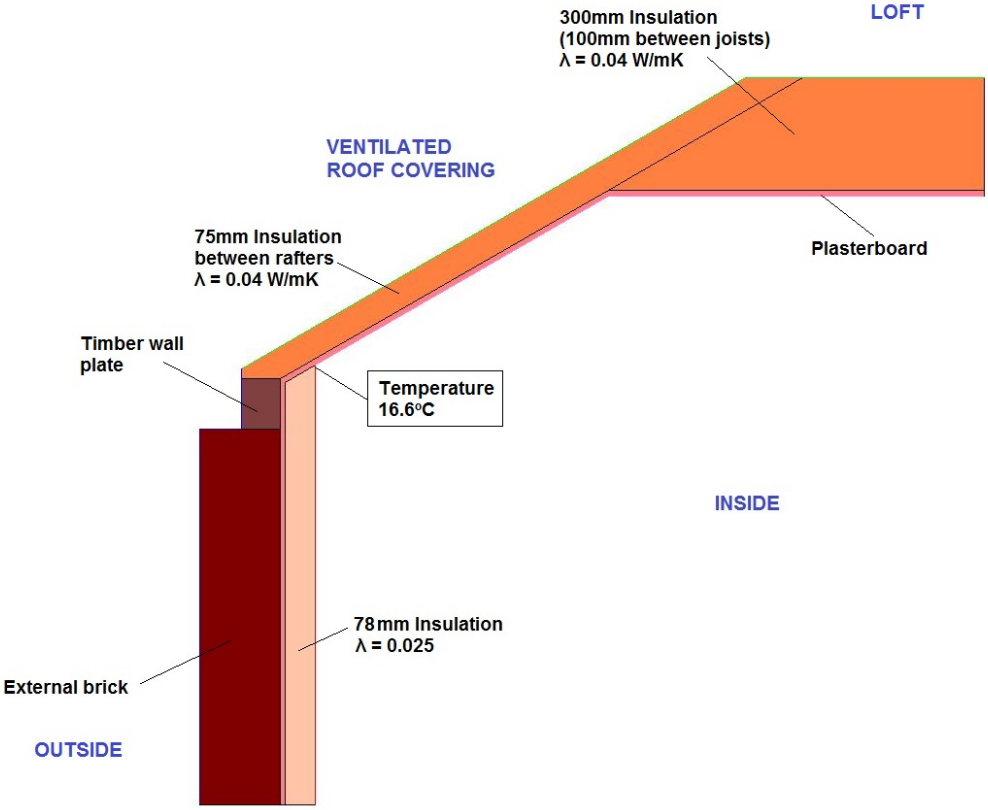


Figure 216: Junction between an insulated cold roof, an insulated warm (sloping ceiling) roof, and a solid wall (typology R8)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 16.6°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.83, which indicates a low risk of mould growth at this junction.

35.2.3. Build-up - (IWI and loft insulation with sloping ceiling insulation below rafters)

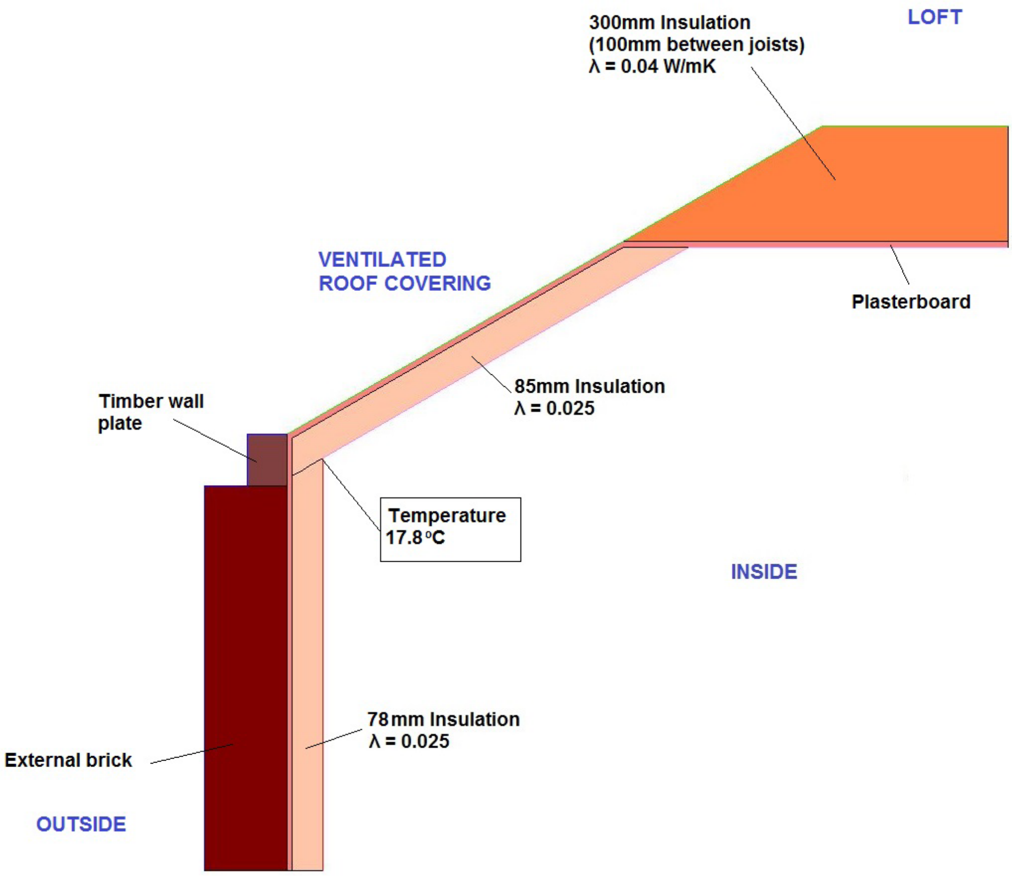


Figure 217: Junction between an insulated cold roof, an insulated warm (sloping ceiling) roof, and a solid wall (typology R8)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 17.8°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.89, which indicates a very low risk of mould growth at this junction.

35.2.4. Build-up - (IWI and loft insulation with sloping ceiling insulation between and below rafters)

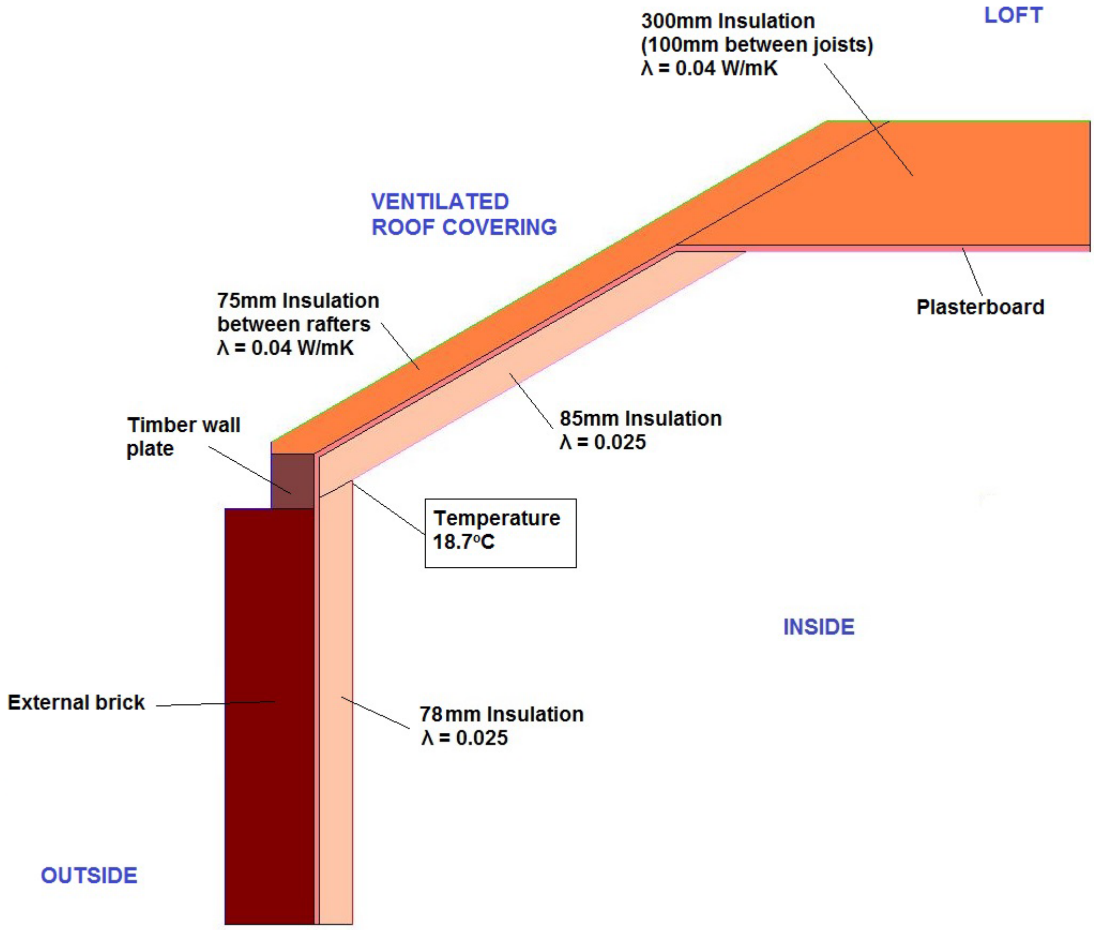


Figure 218: Junction between an insulated cold roof, an insulated warm (sloping ceiling) roof, and a solid wall (typology R8)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 18.7°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.94, which indicates a very low risk of mould growth at this junction.

35.2.5. Build-up - (EWI and loft insulation with no sloping ceiling insulation)

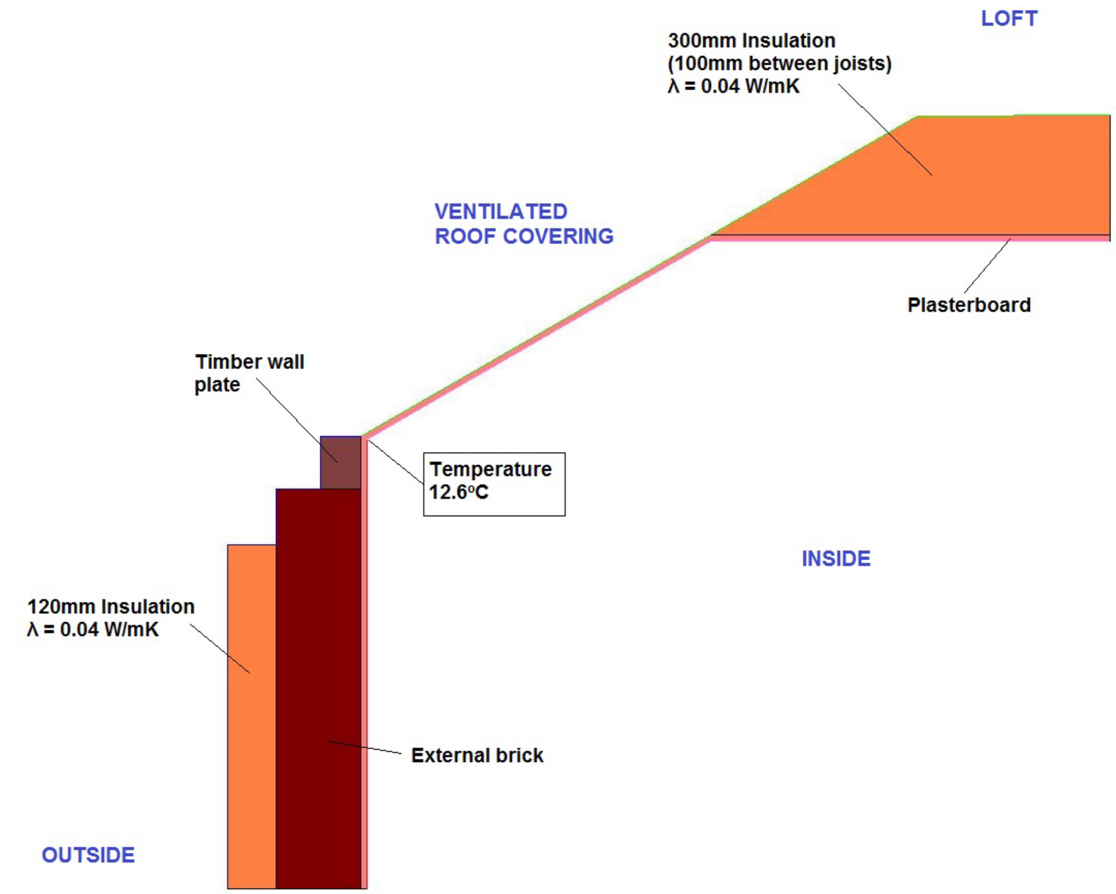


Figure 219: Junction between an insulated cold roof, an un-insulated warm (sloping ceiling) roof, and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 12.6°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.63, which indicates a high risk of mould growth at this junction.

35.2.6. Build-up - (EWI and loft insulation with sloping ceiling insulation between rafters and across wall plate junction)

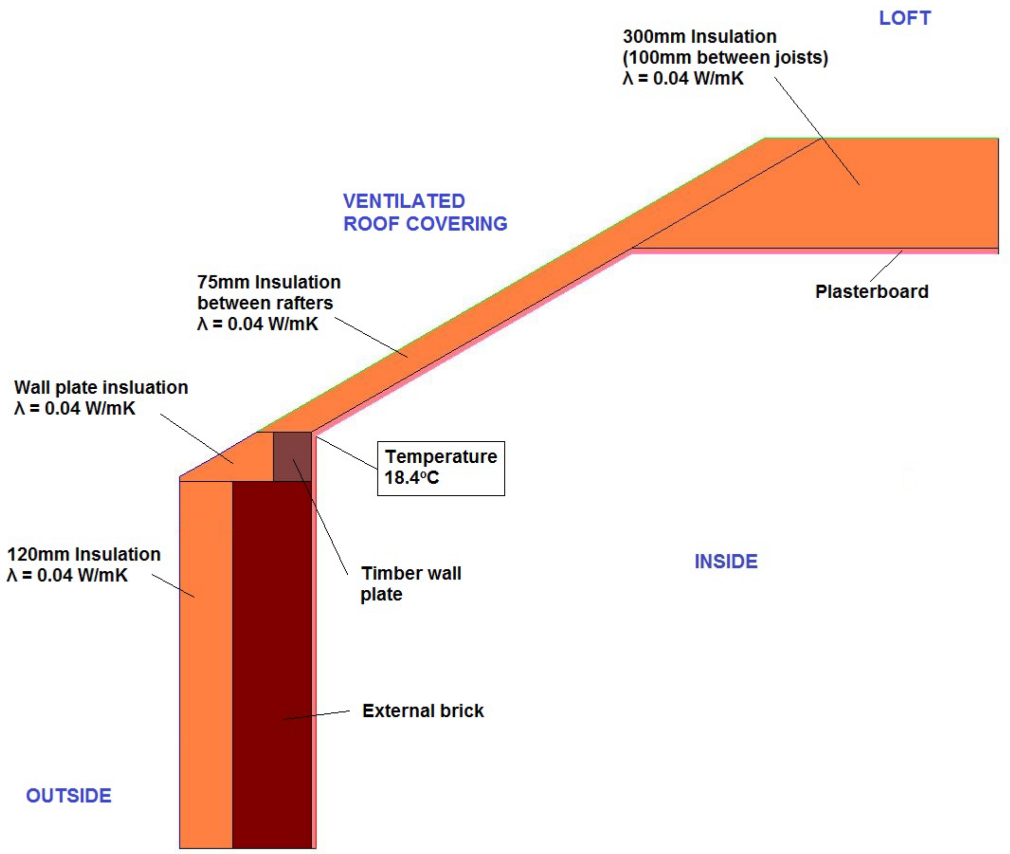


Figure 220: Junction between an insulated cold roof, an insulated warm (sloping ceiling) roof, and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 18.4°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.92, which indicates a very low risk of mould growth at this junction.

35.2.7. Build-up - (EWI and loft insulation with sloping ceiling insulation below rafters)

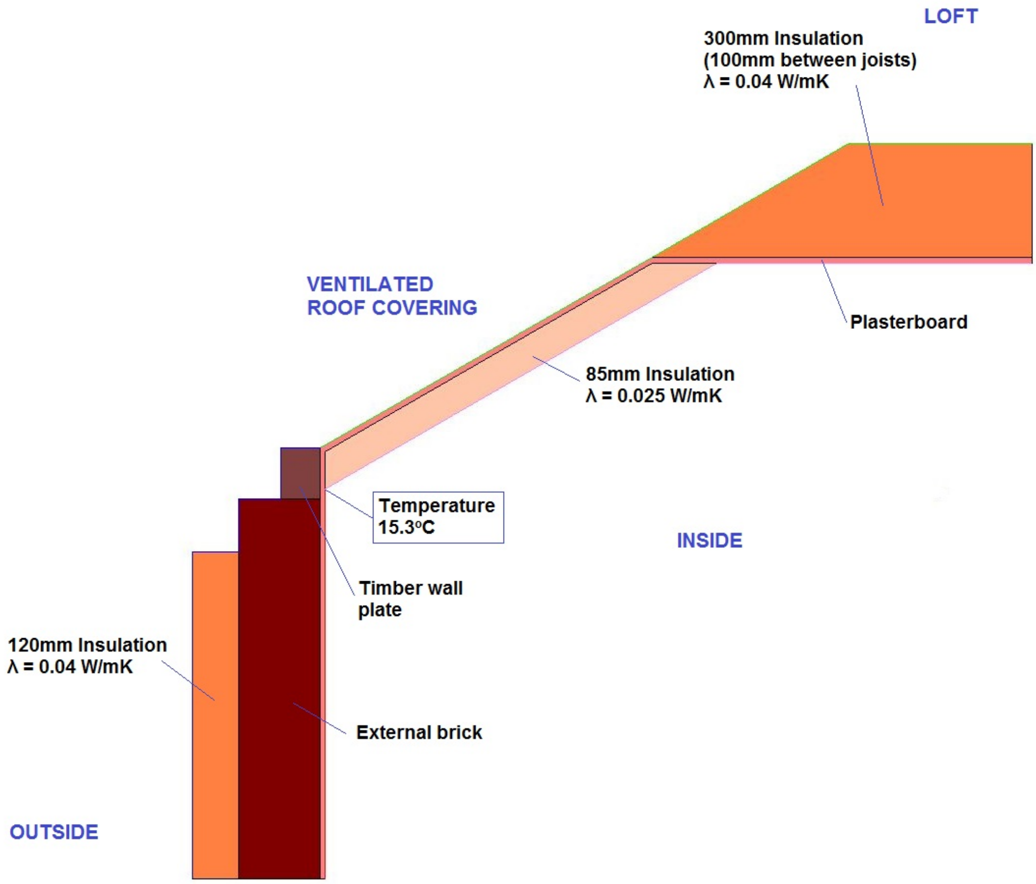


Figure 221: Junction between an insulated cold roof, an insulated warm (sloping ceiling) roof, and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 15.3°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.77, which indicates a low risk of mould growth at this junction.

35.2.8. Build-up - (EWI and loft insulation with sloping ceiling insulation between and below rafters, and across eaves junction)

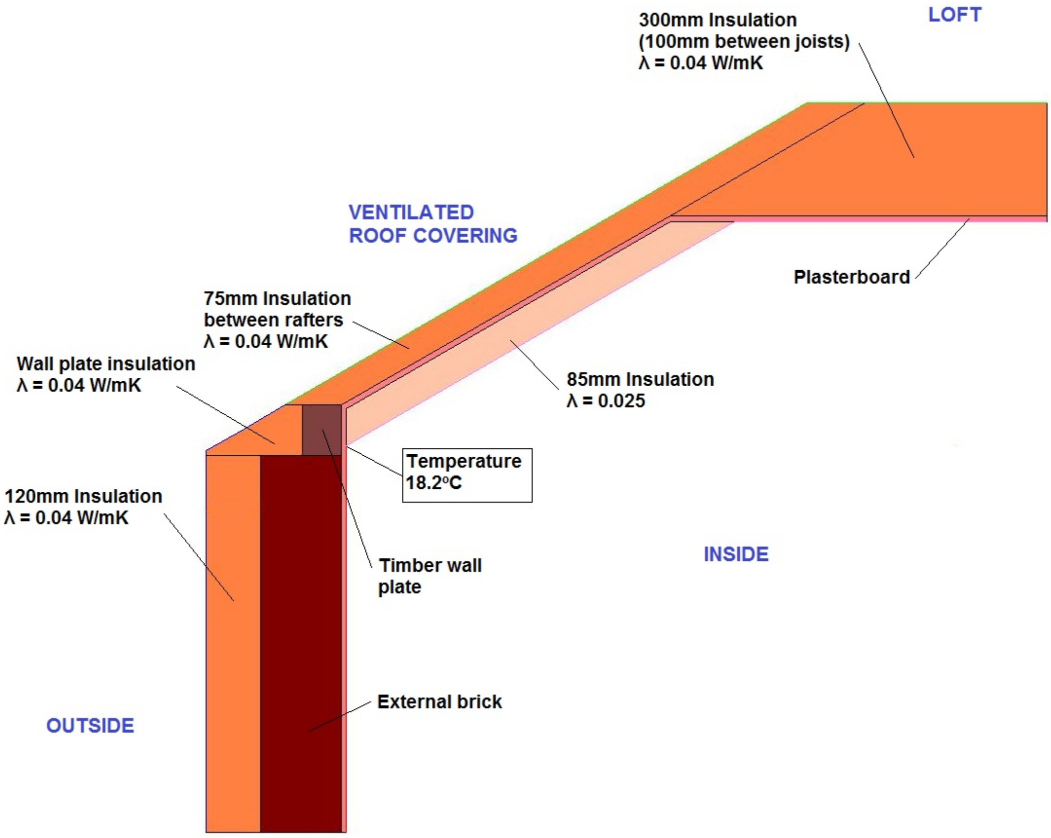


Figure 222: Junction between an insulated cold roof, an insulated warm (sloping ceiling) roof, and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 18.2°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.91, which indicates a very low risk of mould growth at this junction.

35.2.9. Conclusions

- Careful consideration is needed when designing retrofit insulation measures for a junction of this type.

36. Gable at roof

36.1. Gable (insulation at ceiling level) - Wall IWI / EWI

36.1.1. Build-up - (EWI no eaves insulation)

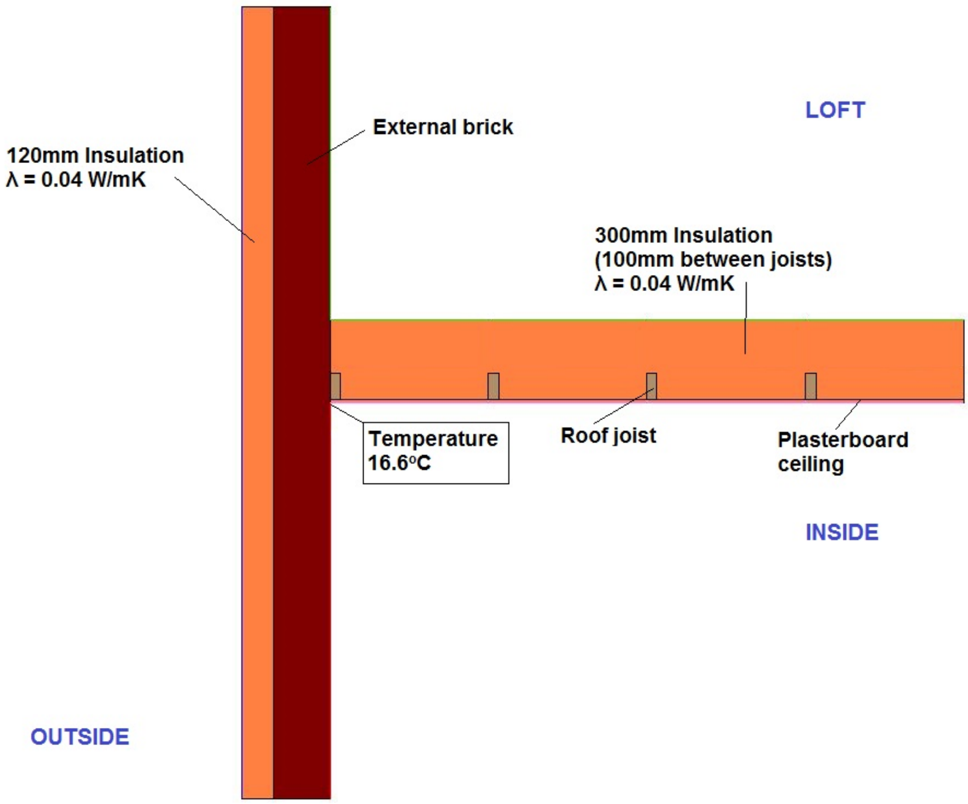


Figure 223: Junction between an insulated cold roof and a solid wall gable (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 16.6°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.83, which indicates a low risk of mould growth.

36.1.2. Build-up - (EWI with eaves insulation)

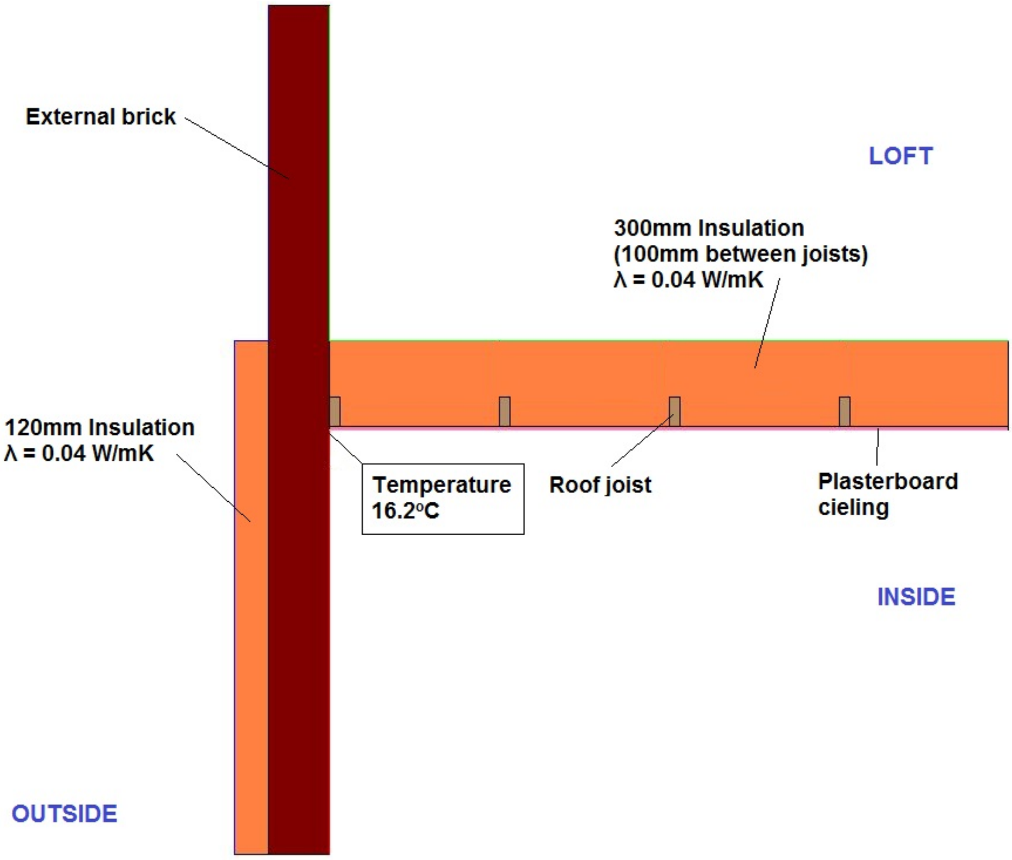


Figure 224: Junction between an insulated cold roof and a solid wall gable (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 16.2°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.81, which indicates a low risk of mould growth at this junction.

36.1.3. Build-up - (EWI with eaves insulation)

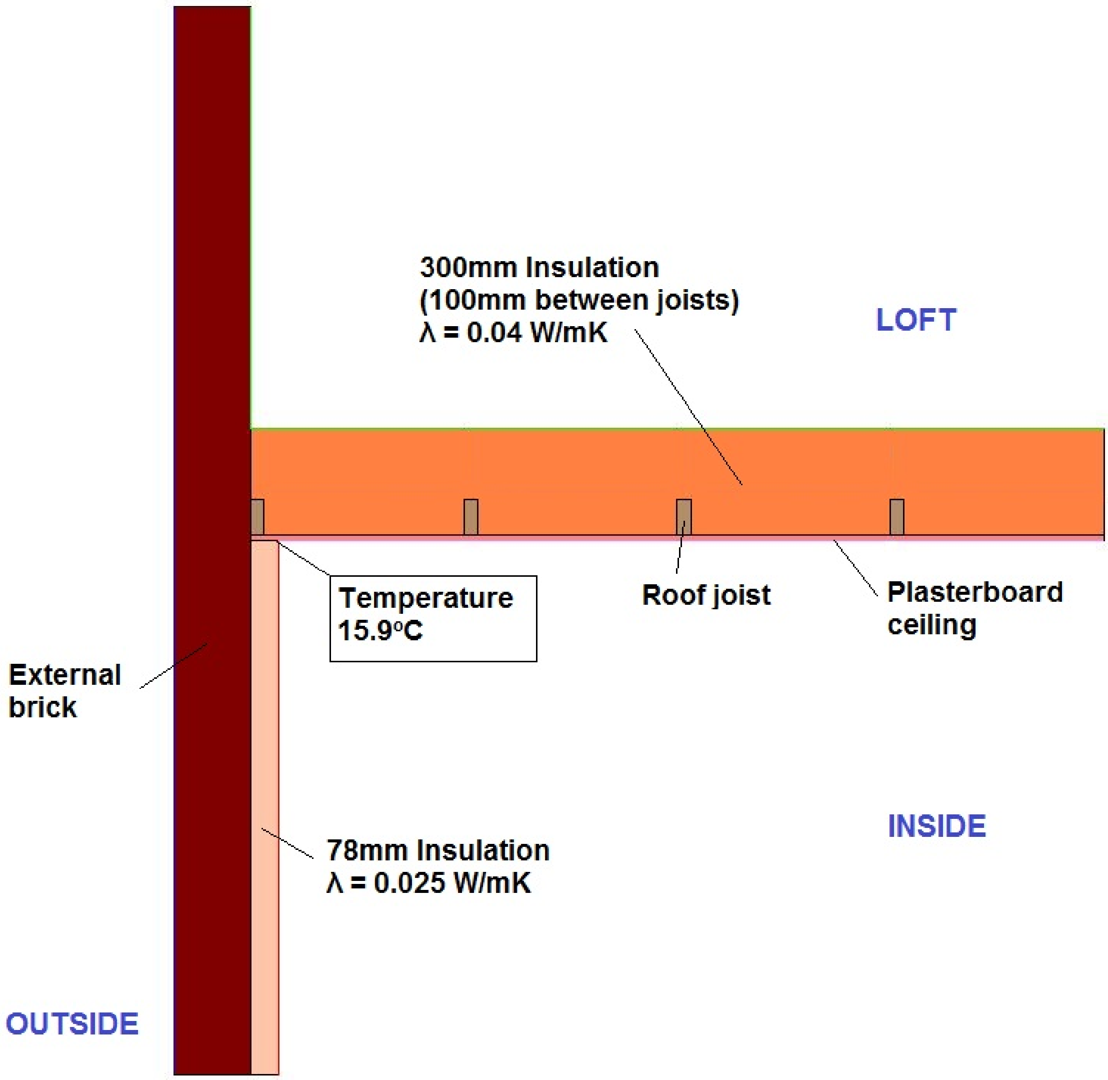


Figure 225: Junction between an insulated cold roof and a solid wall gable (typology R8)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 15.9°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.80, which indicates a low risk of mould growth at this junction.

36.1.4. Conclusions

- Installing either EWI or IWI wall insulation at a gable is low risk in terms of surface temperatures at the junction with a well-insulated loft.

36.2. Gable (insulation at rafter level) - Wall IWI / EWI - Build-up

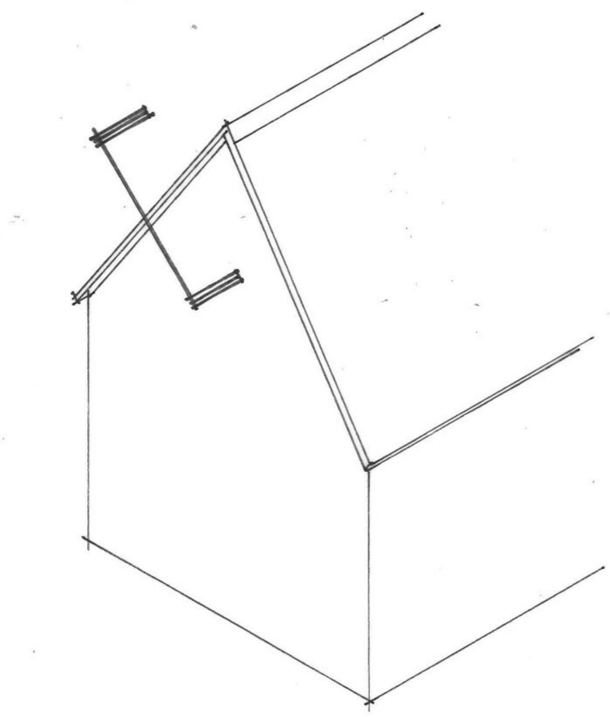


Figure 226: Illustration of section used for gable (insulation at rafter level) analysis

36.2.1. Build-up - (EWI no roof insulation)

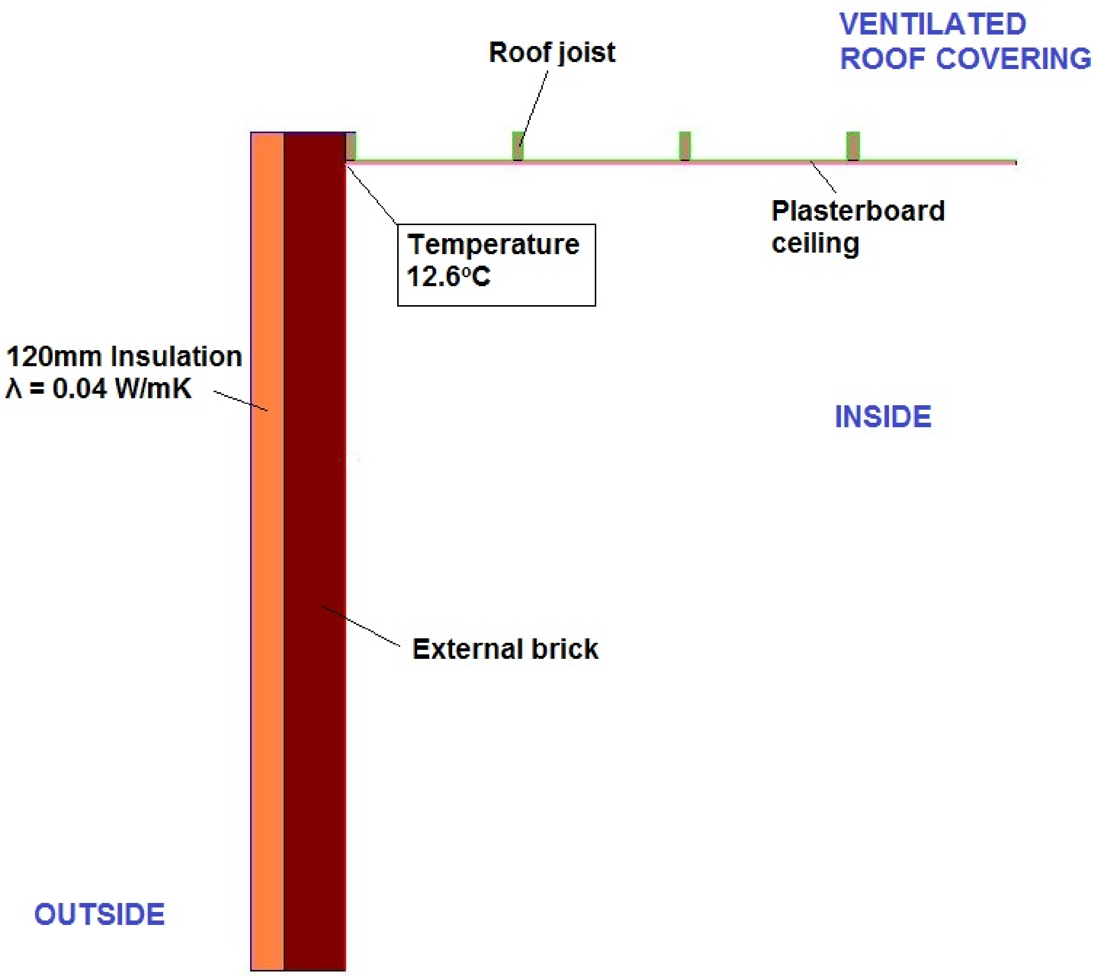


Figure 227: Junction between an un-insulated warm roof and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 12.6°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.63, which indicates a high risk of mould growth at this junction.

36.2.2. Build-up - (EWI with internal roof insulation below joists)

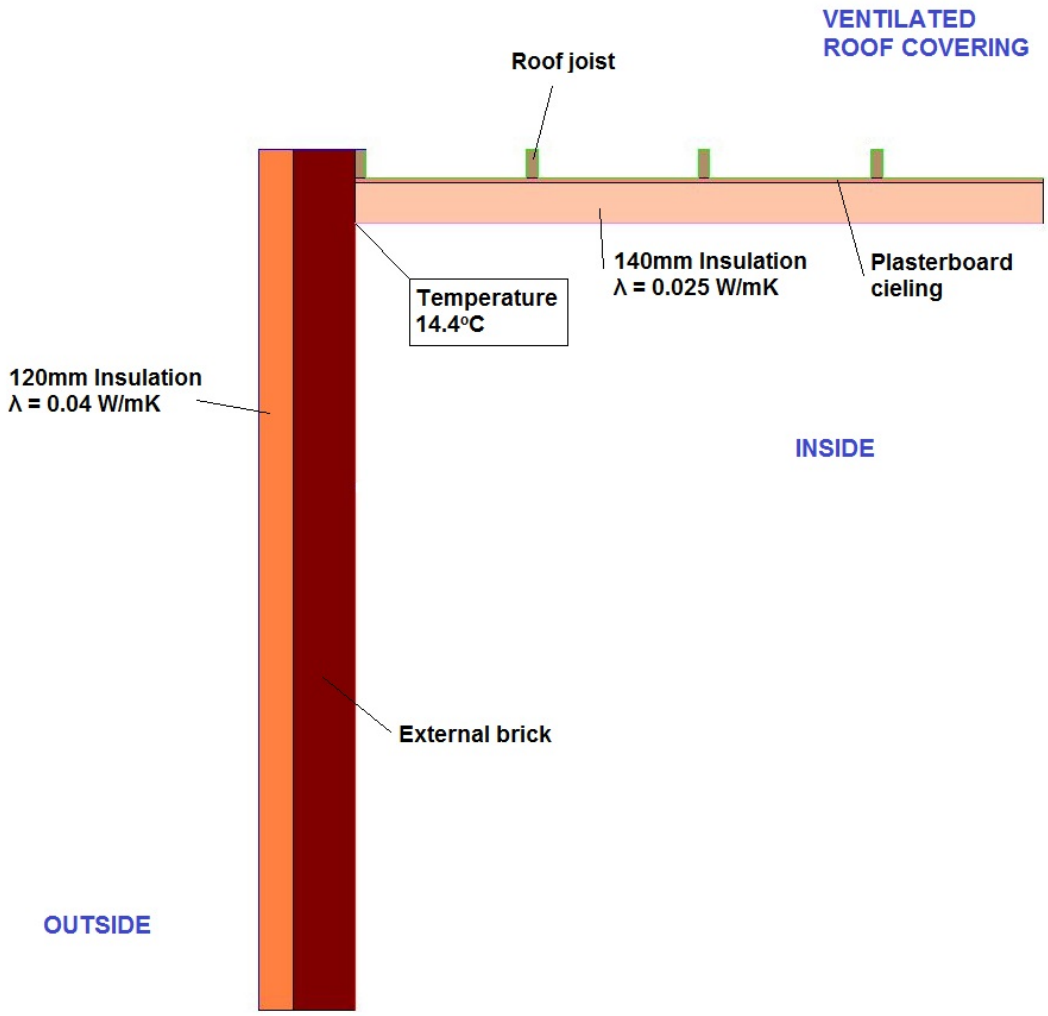


Figure 228: Junction between an insulated warm roof and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 14.4°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.67, which indicates a high risk of mould growth at this junction.

36.2.3. Build-up - (EWI with roof insulation between and below joists)

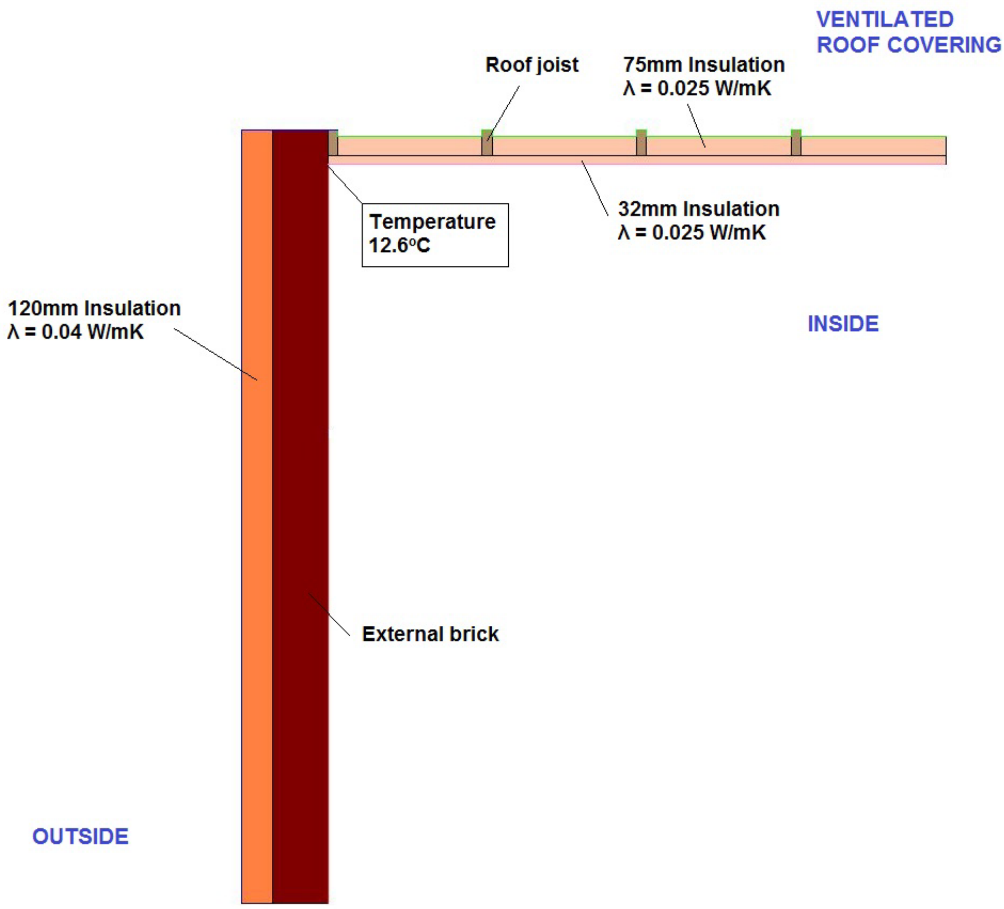


Figure 229: Junction between an insulated warm roof and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 12.6°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.63, which indicates a high risk of mould growth at this junction.

36.2.4. Conclusions

- This construction is vulnerable to mould growth which is difficult to address.

37. Roof

37.1. Cold roof insulation / external wall - Build-up

37.1.1. Build-up - (100mm Loft insulation, no wall insulation)

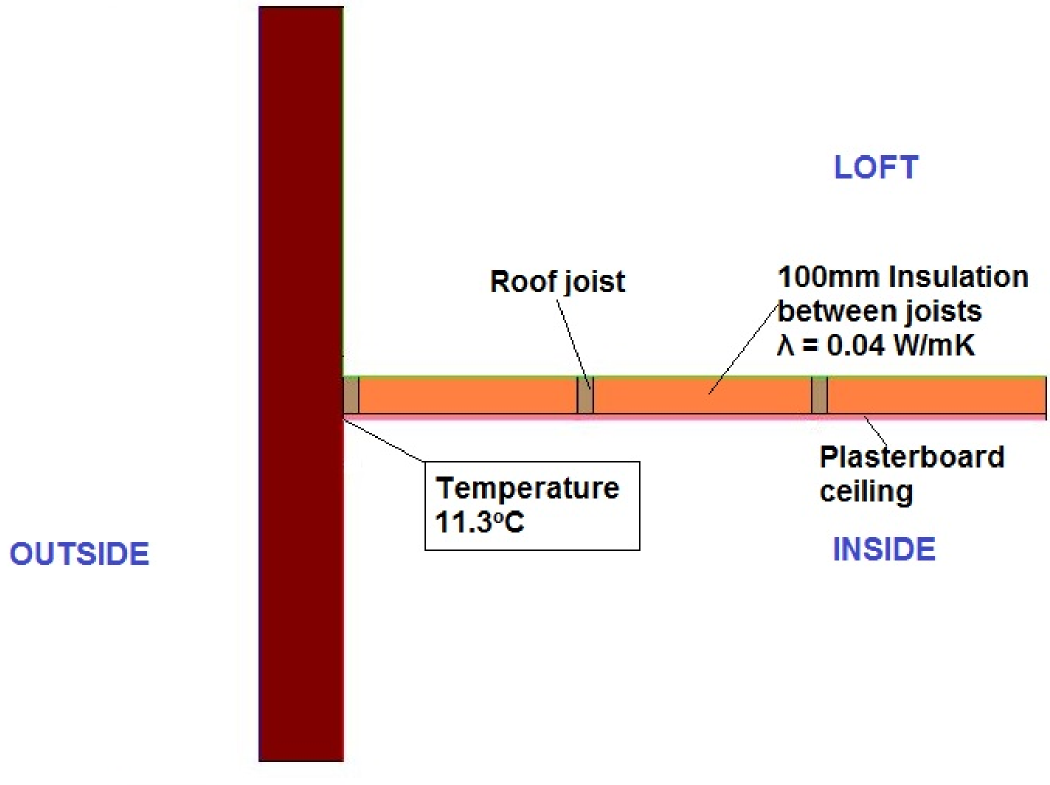


Figure 230: Junction between an insulated cold roof and an uninsulated solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 11.3°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.57, which indicates a very high risk of mould growth at this junction.

37.1.2. Build-up - (300mm Loft insulation, no wall insulation)

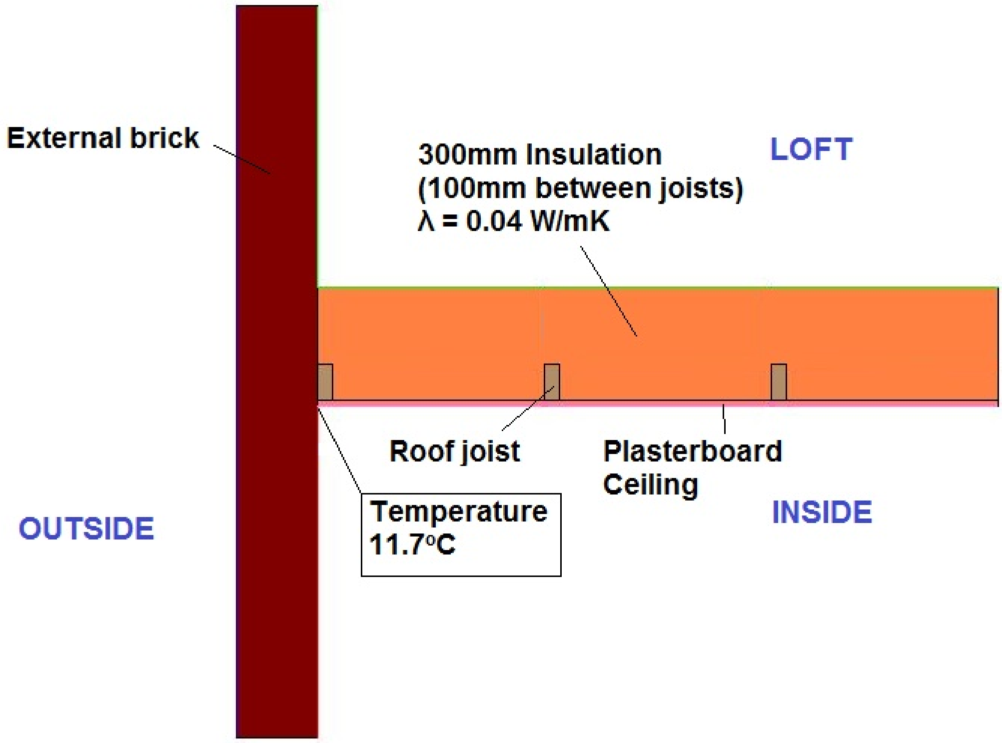


Figure 231: Junction between an insulated cold roof and an uninsulated solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 11.7°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.59, which indicates a very high risk of mould growth at this junction.

37.1.3. Conclusions

- This junction is vulnerable to mould growth which is difficult to address.

37.2. Loft Hatch - Build-up

37.2.1. Build-up - (300mm Loft insulation, no loft hatch insulation)

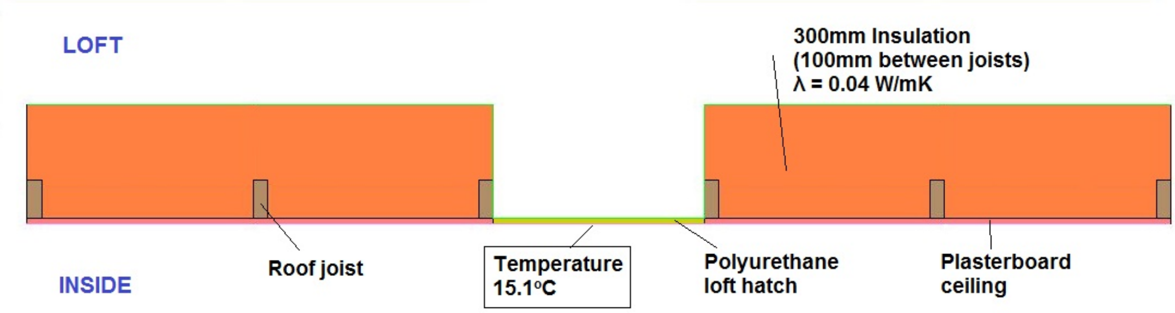


Figure 232: Insulated loft with un-insulated loft hatch

- Results Analysis

Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (centre of loft hatch) (T_{si}) is 15.1°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.76, which indicates a low risk of mould growth at this junction.

37.2.2. Build-up - (300mm Loft insulation, 50mm loft hatch insulation)

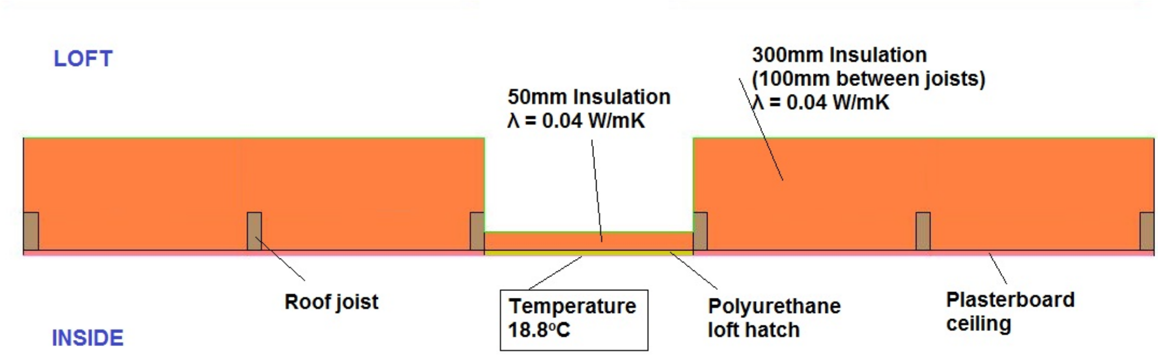


Figure 233: Insulated loft with insulated loft hatch

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (centre of loft hatch) (T_{si}) increases to 18.8°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.94, which indicates a very low risk of mould growth at this junction.

37.2.3. Conclusions

- Insulating the loft hatch is very effective to reduce mould growth risk.

38. Other

38.1. External Meter Box

38.1.1. Build-up - (EWI no insulation behind meter box)

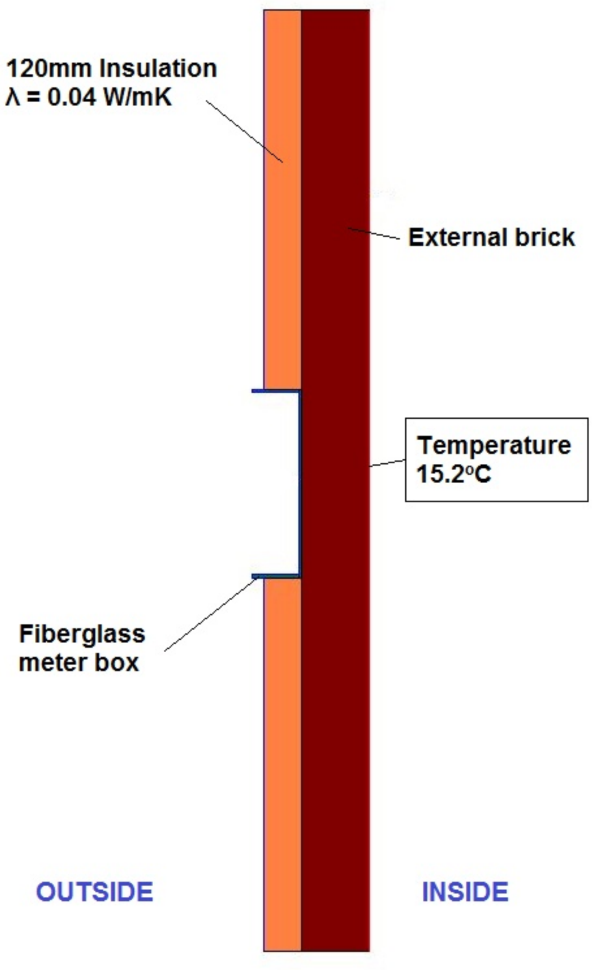


Figure 234: Junction between an external meter box and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (wall behind meter box) (T_{si}) is 15.2°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.76, which indicates a low risk of mould growth at this junction.

38.1.2. Build-up - (EWI with insulation behind meter box)

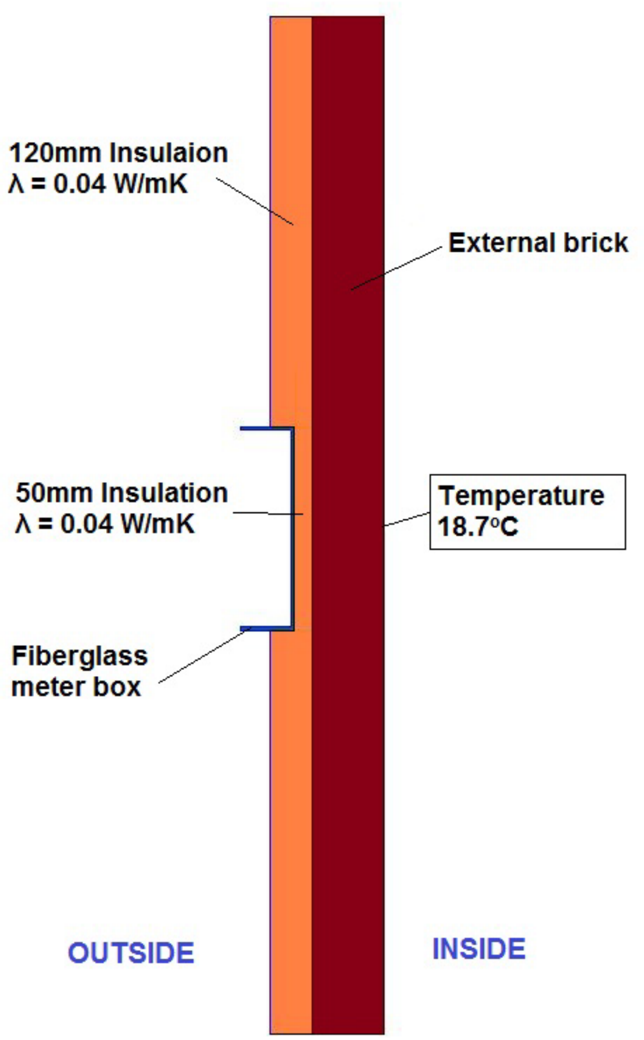


Figure 235: Junction between an external meter box (insulated behind) and a solid wall (typology R9)

- Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (wall behind meter box) (T_{si}) increases to 18.7°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.94, which indicates a very low risk of mould growth at this junction.

38.1.3. Conclusions

- Insulating behind a meter box if possible is very effective to reducing mould growth risk.

39. 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	∅	∅	0.13	20	~	∅	∅	∅	∅
	1	Softwood	-	150	400	0.73	1500	0.09	200	~	60	575	-	-
2 Chip board	3	Chipboard	-	18	600	∅	∅	0.14	15	~	∅	∅	∅	∅
	1	Chipboard	-	18	600	0.5	1500	0.11	70	~	90.0	400	-	-
3 Plywood	3	Plywood	-	9	500	∅	∅	0.13	70	~	∅	∅	∅	∅
	1	Plywood board	-	9	500	0.5	1500	0.10	700	~	75	350	-	-
4 OSB	3	OSB	-	9	650	∅	∅	0.13	30	~	∅	∅	∅	∅
	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	∅	∅	1.15	60	~	∅	∅	∅	∅
	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	∅	∅	1.35	60	~	∅	∅	∅	∅
	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	∅	∅	1.15	60	~	∅	∅	∅	∅
	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	∅	∅	0.16	6	~	∅	∅	∅	∅
	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	∅	∅	0.57	10	~	∅	∅	∅	∅
	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	∅	∅	2	50	~	∅	∅	∅	∅
	1	Generic Gravel	-	150	1400	0.3	1000	0.70	1	~	5	50	-	-
11 Brick wall	3	Solid brick wall	-	215	1700	∅	∅	0.77	45	~	∅	∅	∅	∅
	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	∅	∅	0.04	60	~	∅	∅	∅	∅
	1	EPS (density: 15 kg/m3)	-	87.5	15	0.95	1500	0.04	30	~	-	-	-	-
13 XPS	3	XPS	-	30	30	∅	∅	0.03	50	~	∅	∅	∅	∅
	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	∅	∅	0.025	50	~	∅	∅	∅	∅
	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	∅	∅	0.04	1	~	∅	∅	∅	∅
	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	∅	∅	0.17	400000	∅	∅	∅	∅	∅
	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	∅	∅	200	999999	∅	∅	∅	∅	∅
	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	∅	∅	0.17	300000	∅	∅	∅	∅	∅
	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	∅	∅	0.17	2000	∅	∅	∅	∅	∅
	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	∅	∅	0.21	4	~	∅	∅	∅	∅

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 (mm)	ρ_{bulk} (kg/m3)	w_{max} (m3/m3)	cp (J/kg.K)	λ (W/m.K)	μ (-)	s_d (m)	w80 (kg/m^3)	w_f (kg/m^3)	A ($kg/m^2\sqrt{s}$)	A ($kg/m^2\sqrt{h}$)
	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	Ø	Ø	0.21	4	~	Ø	Ø	Ø	Ø
	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	Ø	Ø	0.3	9.8	~	Ø	Ø	Ø	Ø
	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	Ø	Ø	0.8	6	~	Ø	Ø	Ø	Ø
	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	Ø	Ø	0.23	30	~	Ø	Ø	Ø	Ø
	2	**Cement board (North American database)**	-	**25**	**1130**	**0.48**	**840**	**0.26**	**28**	~	-	-	-	-
25 Bitumen	3	Bitumen	-	25	110	Ø	Ø	0.23	50000	Ø	Ø	Ø	Ø	Ø
	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	Ø	Ø	0.088	1	~	Ø	Ø	Ø	Ø
	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	Ø	Ø	0.278	1	~	Ø	Ø	Ø	Ø
	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	Ø	Ø	0.9	1	~	Ø	Ø	Ø	Ø
	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	Ø	Ø	0.9	1	~	Ø	Ø	Ø	Ø
	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

40. 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	Where heat is transferred via convection in a building

bypass	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/m²K).
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.

41. 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.

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'. BSI Standards Publication.

May, N. & Sanders, C. (2014). Moisture Risk Assessment and Guidance. Sustainable Traditional Building Alliance and Department of Energy & Climate Change.

Rirsch, E., Zhang, Z. (2012). Energy Saving from Water Repellents. Retrofit 2012. University of Salford.

Ward, T. I. (2006). Information Paper 1/06: Assessing the effects of thermal bridging at junctions and around openings. BRE.