Department for Energy Security & Net Zero

Loughborough University

Building Energy Research Group (BERG)

DEEP Report 6.03

Moisture Risk from Internal Wall Insulation (IWI)

October 2024

Prepared by Building Energy Research Group (BERG), Loughborough University

Dr Kostas Mourkos,
Professor David Allinson,
Dr Eirini Mantesi.

Any enquiries regarding this publication should be sent to us at: EnergyResearch@energysecurity.gov.uk

Contents

Executive Summary

This work contributes to Objective 3 of the Demonstration of Energy Efficiency Potential (DEEP) research project, “To use … models to evaluate the benefits of adopting a whole house approach to retrofit and the unintended consequences of neglecting such an approach”. Specifically, this report focuses on improving modelling of moisture risk from installing internal wall insulation (IWI).

Moisture accumulation in the walls of buildings can lead to severe damage and can affect the health of occupants. There are concerns that retrofitting homes with IWI will increase moisture risk. It is difficult to measure moisture risk in the field as moisture can accumulate over many years and problems can remain hidden within the fabric of a building. Therefore, hygrothermal simulation was used to analyse the moisture profile of solid brick[1] walls, over a decade of real weather, in two locations with differing exposure to wind driven rain.

A validated hygrothermal software tool was used to simulate the walls, but there is no standardised way to define if a building has a moisture risk or not. There will always be inherent uncertainty in boundary conditions[2], the condition of the building, and in the thermophysical properties of the construction materials that make an absolute measurement of moisture risk difficult. However, it is possible to determine if risk is increased by the installation of IWI.

To assess moisture risk in DEEP, a robust method to simulate the ***relative*** risk from installing IWI was developed. Different thickness of IWI installed on a solid brick wall were compared to the case of the uninsulated wall. The use of vapour permeable wood-fibre IWI was compared with vapour impermeable EPS IWI. Based on these simulations, installing IWI always led to an increased moisture risk, even when only thin levels of insulation were applied e.g., at a U-value of 1.1 W/m²K. This was not unexpected as adding IWI will always make the wall colder than it would have been in winter and therefore the relative humidity of the wall at critical locations will be higher, even if the moisture content remains the same.

Increasing the thickness of the IWI increased the relative moisture risk in all cases (see figure below). No safe limit exists for moisture risk and so a threshold insulation thickness cannot be quantified. However, the results for wood fibre insulation showed that the relative moisture risk increased more rapidly below a U-value of about 0.8 W/(m²·K) [3]. This is similar to the threshold U-value of a renovated wall, according to the building regulations [1], of 0.7 W/(m²·K)[4]. However, long-term field work is needed to determine a suitable threshold of risk/benefit in different weather/exposure locations before thinner IWI can be recommended.

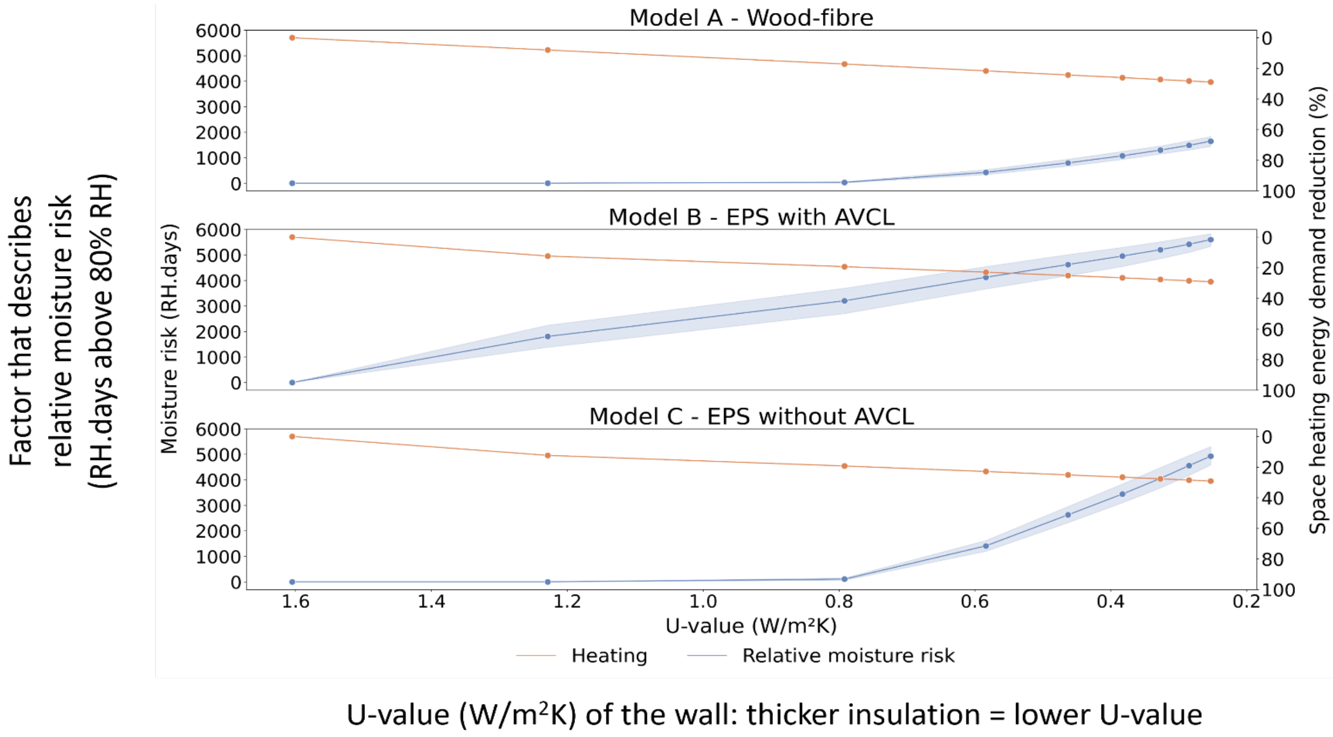
---

[1] Solid brick walls comprise two layers of brick with a micro cavity that cannot be filled with insulation.

[2] For example, the results were sensitive to assumptions about indoor RH.

[3] 30 mm of wood fibre insulation was required to achieve this U-value.

[4] In the building regulations it is also stated that the 0.7 value can be lowered due to interstitial and surface condensation; compliance with Part C is required in this case.



The wood-fibre vapour permeable IWI produced a relatively lower risk than the EPS with an air and vapour control layer (AVCL) vapour impermeable IWI. When the EPS was simulated without the AVCL, the relative risk for EPS was reduced as the wall could dry out to the internal environment. The lowest relative risk was still for the wood-fibre vapour permeable IWI. Changing the wall orientation or changing the brick properties in the simulations did not significantly change the relative risk ranking of different IWI solutions. The impact of orientation on moisture risk was minimal when moisture risk was minimal, but orientation should be considered when the moisture risk is higher due to wind driven rain exposure. The water absorption coefficient of bricks on its own was not a good indicator of moisture risk. The brick properties were not important at lower moisture risk. The use of a "brick cream" coating to waterproof bricks was not justified by this research as it only reduced the moisture risk when moisture risk was already relatively high.

Homes with a higher internally generated moisture load[5] will have a higher moisture risk. It would be sensible to ensure homes can be adequately ventilated to remove moisture from activities such as cooking, bathing, and laundry. This highlights the importance of holistic retrofit that improves ventilation to reduce moisture load. Overall, the inherent variability in the weather over the ten years modelled in this work had a strong impact on the moisture risk in some cases more than others. The use of weather files with ten-years of recent weather observations (Recent Weather Decade or RWD files) is therefore recommended over a weather file consisting of data of one only year. The use of thinner IWI is promising, and future investigations should focus on the interplay between energy savings and moisture risk for different thicknesses of insulation.

---

[5] Moisture is generated from respiration, perspiration, bathing, laundry, and cooking.

1. Introduction

This report describes work carried out for the Department for Energy Security and Net Zero (DESNZ) under their Demonstration of Energy Efficiency Potential (DEEP) research project. This work contributes to Objective 3, as stated in the invitation to tender (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/837866/Invitation-to-Tender-for-Demonstration-of-Energy-Efficiency-Potential-DEEP.pdf): "To use … models to evaluate the benefits of adopting a whole house approach to retrofit and the unintended consequences of neglecting such an approach". Specifically, this report focuses on modelling moisture risk from installing internal wall insulation (IWI).

Solid wall insulation can significantly improve the energy performance of existing homes [2]. IWI is sometimes the only viable solution as there are many places where external wall insulation is not practical e.g. external wall insulation cannot be installed in some conservation areas [3].

There are concerns that retrofitting homes with IWI will increase moisture risk. An internally insulated wall is thermally decoupled from the indoor environment and so will be colder in winter than an uninsulated wall or a wall with external wall insulation. Reducing the temperature of the wall will increase the relative humidity (RH) of the air at the interfaces of materials and in their pores, increasing condensation. The accumulation of moisture in the walls of buildings can lead to severe damage, such as the rotting of structural timber floor joists that are embedded in the wall [4] and mould that grows on damp walls can affect the health of occupants [5]. Previous modelling work (in particular, dynamic hygrothermal simulation) shows clearly that IWI[6] can increase the risk of moisture related damage [4,6].

There is, at present, no universally accepted method or criteria for accurately predicting that moisture problems will occur. The outputs of models have a high degree of uncertainty because of the aleatory uncertainty in indoor environment (temperature and RH) and outdoor environment (air temperature, RH, rainfall, windspeed, and wind direction) both of which influence moisture risk to a great extent [6]. The indoor environment is influenced significantly by the occupants' moisture generation, ventilation, and heating practices. These practices vary considerably from time to time and from home to home, and so are difficult to represent in models.

This report explains the development of a more robust moisture risk assessment method for the DEEP project (Section 2), details the case study walls that are assessed for moisture risk (Section 3), details of the modelling inputs that were used (Section 4), and provides comparative results (Section 5), before discussing the outcome and drawing conclusions (Section 6).

[6] Insulation materials investigated included cellulose fibres, aerogel blankets, phenolic and polyurethane foam.

2. Moisture risk assessment method

Moisture risks were predicted using WUFI Pro 6.5 [7]. This software tool predicts the moisture content and temperature profiles through building elements (such as a wall or a roof) by dynamic, one-dimensional, hygrothermal simulation, in line with BS EN 15026:2007 [8]. The user must input details of the building element construction and materials, indoor environment, and external environment (weather). The results of the simulation must then be compared with some externally defined criteria to determine if there is a moisture risk.

The modelling inputs used for this project are described in detail in Section 4. Material properties were obtained from WUFI Pro's database. The indoor environment was modelled according to the relative model in EN 15026 [8] where indoor temperature and humidity are correlated to the outdoor temperature. The outdoor environment was represented using the Recent Weather Decade (RWD) files developed as part of the DEEP project (see DEEP Project Report 6.01 [9]) This is in line with BS EN 15026:2007, which states that the most suitable option is to use actual weather data from at least ten years.

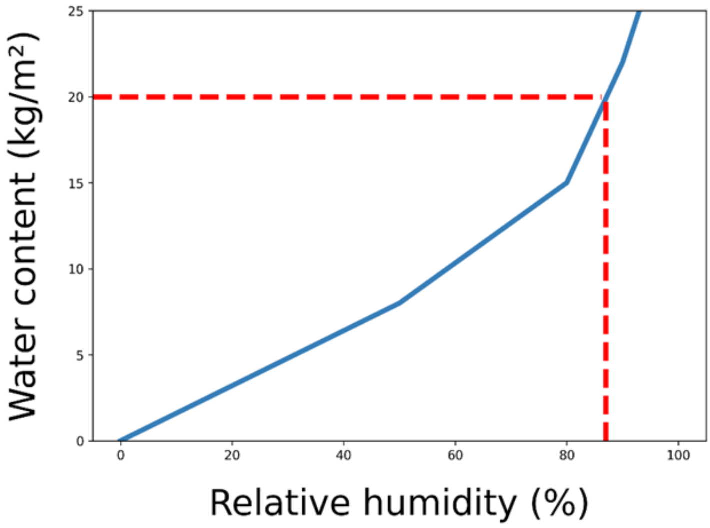
There is no standardised way to define if a building has a moisture risk or not and BS EN 15026:2007 does not include any criteria. Some guidance is provided by the Fraunhofer Institute of Building Physics in Germany [6]. Firstly, moisture must not accumulate over time such that the model reaches a dynamic equilibrium; and secondly, three risk thresholds, Criterion 1-3, are defined:

1. RH at critical locations[7] should drop below 80% within the first six months of the simulation.
2. RH at critical locations should exceed the threshold value of 80% only occasionally (i.e., less than a month) to ensure good drying.
3. Moisture content in timber should be less than 20% of the mass of the timber ensuring that rot is not an issue for timber elements.

Criterion 3 is used to assess whether floor joists that are supported by the wall would be prone to timber rot. The floor joists are not normally modelled explicitly and so the moisture content of the wood is calculated from the RH at the point in the wall where the wood is supported, after the method described by Arregi et al. [10]. The moisture storage function for soft wood, obtained from the WUFI Pro database, gave a RH of 87% for a moisture content of 20% (Figure 1).

[7] A critical location in a construction is the interface between adjacent layers where a large increase in RH is expected due to a sudden drop in temperature (e.g., at the interface between masonry and insulation).

Figure 1: Moisture storage function for soft wood showing 20% moisture content at 87% RH



The problem with these deterministic pass/fail criteria is that the result is very sensitive to the chosen boundary conditions and the defined threshold is not precise. The resulting binary risk is uncertain, and it would be misleading to state that any wall was moisture safe or not. Therefore, to determine the moisture risk in DEEP, a new metric was developed to compare the ***relative*** risk from installing IWI. Using this metric, the relative risks from different thicknesses of IWI installed on a solid brick wall were compared to the case of the uninsulated wall, and the relative risk from using vapour permeable wood-fibre IWI was compared with the relative risk from using vapour impermeable EPS IWI.

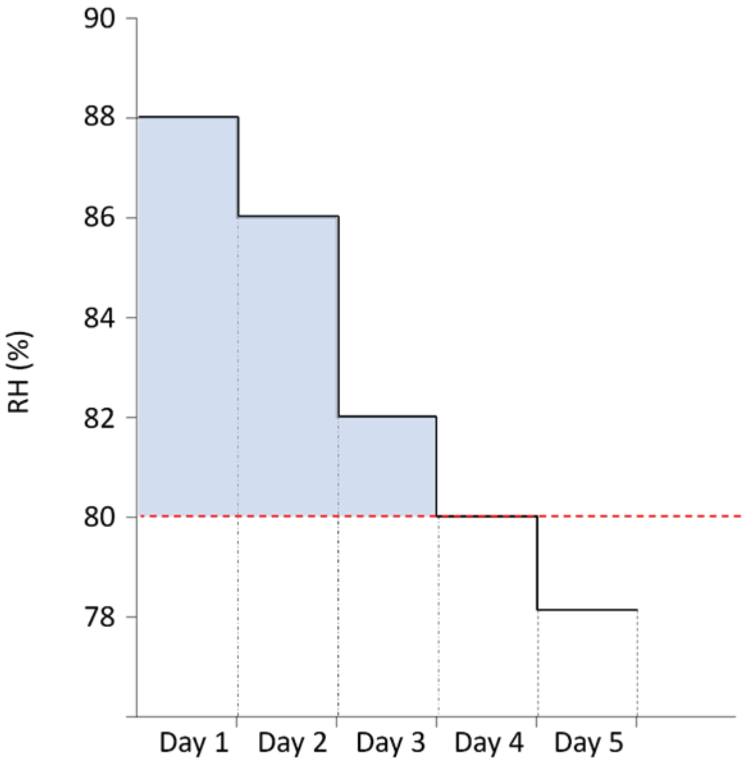
The new metric is named "moisture risk RH.days". Moisture risk RH.days describe the time-weighted exceedance of 80% RH at critical locations: at the interface between brickwork and plaster for the uninsulated walls, and on the cold side of the insulation (towards the exterior side of the wall) for the insulated walls. The higher the number of moisture risk RH.days the higher the risk of moisture problems occurring.

Moisture risk RH.days are calculated as the sum of the exceedance of the daily average RH above a threshold of 80% in units of RH.days. This accounts for both the amount of daily RH above the threshold value of 80%, and the time period that this exceedance takes place. To illustrate how this criterion works, Figure 2 displays a hypothetical daily average RH profile over five days where RH ranges from 78 to 88%. Moisture risk RH.days[8] (which are highlighted in light blue) are computed as follows:

$$(88-80)\times 1 + (86-80)\times 1 + (82-80)\times 1 = 16\ RH.days \qquad \text{Equation 1}$$

[8] Note that the maximum theoretical value of moisture risk RH.days is (100-20) x 365 = 7300.

Figure 2: Hypothetical average daily profile of RH over five days



The moisture risk RH.days were used to compare the relative moisture risk for the case-study walls under different conditions. Walls with a lower moisture risk RH.days value will have a lower moisture risk. This allows different walls in different scenarios to be ranked and compared. All results are given in Section 5.

For the modelling work shown in this report, the results are given in moisture risk RH.days. These results were compared with those using the risk thresholds, Criterion 1-2, described above. These criteria are designed for assessments that follow a pass/fail approach therefore hindering comparisons between different constructions, but the use of moisture risk RH.days resolves this issue. Moreover, when any case failed one of these criteria, the moisture risk-days were higher than in any cases where the same criterion passed. This indicates a level of agreement between the methods when *ranking* the performance of different walls in different locations: a wall that failed against the criteria would never be ranked as being better than one that passed.

3. Case-study walls

Case study walls were assessed by hygrothermal simulation for two different locations using London and Manchester RWD files. These two locations differ not only geographically but also in terms of the Wind Driven Rain (WDR) Exposure: on the WDR exposure map in Approved Document C London and Manchester belong in category 1 (Sheltered) and 2 (Moderate) respectively [11].

The walls were assessed without insulation and for four different target U-values as shown in Table 1. The actual U-value differs slightly from the target U-value because insulation products are only available in fixed thicknesses and so the thickness required to at least achieve the U-value target was selected.

Table 1: Case-study walls

Scenario	Target U-value W/(m^2·K)	Actual U-value W/(m^2·K) (thickness[1]) IWI A Wood-fibre	IWI B EPS with AVCL
Uninsulated wall	-	1.61 (no insulation)	
IWI 1	1.1	0.96 (20 mm)	0.98 (10 mm)
IWI 2	0.7	0.67 (40 mm)	0.66 (30 mm)
IWI 3	0.5	0.42 (80 mm)	0.50 (50 mm)
IWI 4	0.3	0.27 (140 mm)	0.28 (110 mm)

[1] The thickness of the insulation material to achieve the displayed U-values is shown in brackets.

The uninsulated wall (Figure 3) consisted of two brick layers with an unvented air layer between them, to represent the micro cavity that exists between the bricks in a solid brick wall, [12] and a plaster finish. Two types of insulation were used in the retrofitted walls. IWI A – wood-fibre (Figure 4) had lime plaster on the inner side of the interior brick to adhere the wood-fibre insulation boards and a lime plaster finish. IWI B – EPS with AVCL (Figure 5) had the EPS insulation boards attached to the walls using plaster dot and dab (modelled as an unvented air layer), an Air and Vapour Control Layer (AVCL) on the warm side of the insulation (as in a laminated insulation board) and a plaster board finish. The mortar joints in the brickwork and any joints in insulation were not explicitly modelled in the 1-dimensional simulations.

Figure 3: The uninsulated solid brick wall with micro-cavity and plaster finish

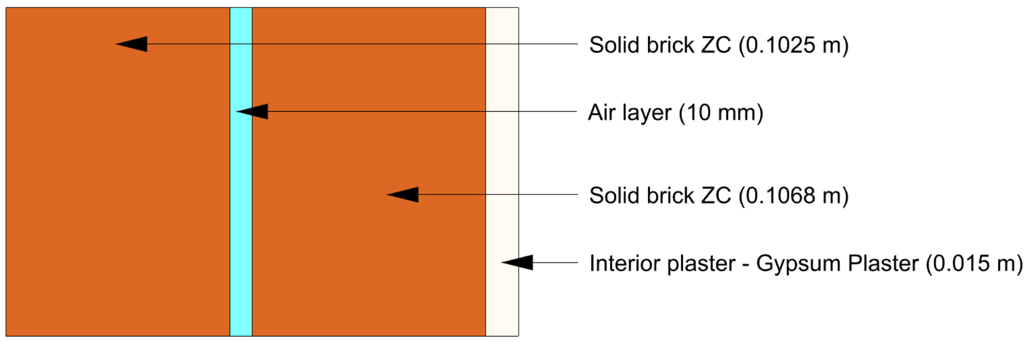


Figure 4: The insulated wall with IWI A – Wood-fibre

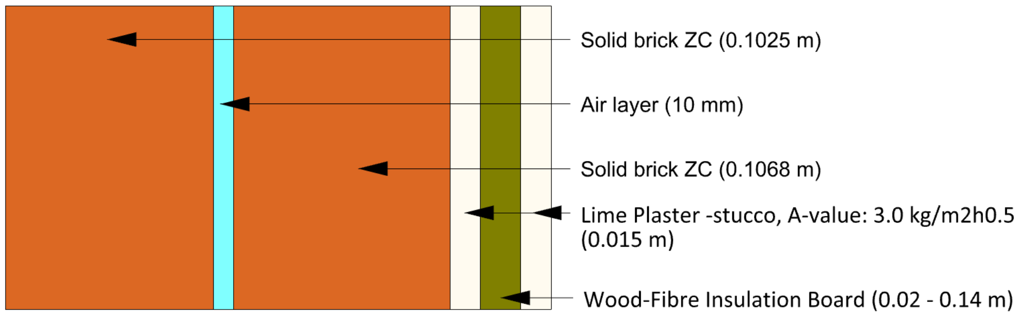
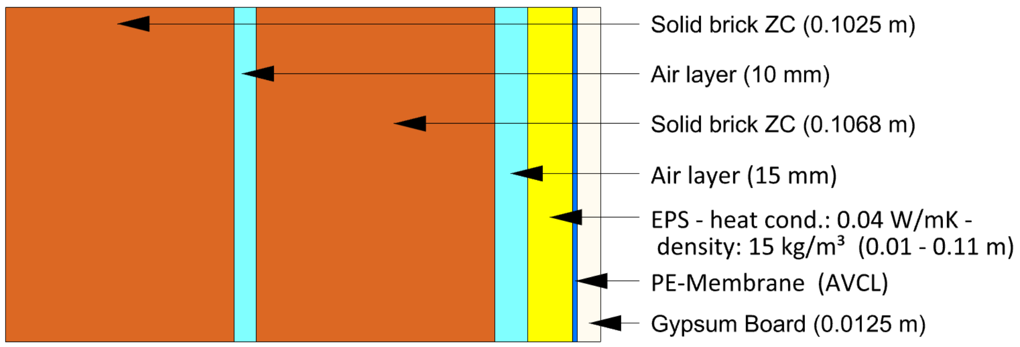


Figure 5: The insulated wall with IWI B - EPS with AVCL



4. Modelling inputs

Recent Weather Decade files for London (Figure 6) and Manchester (Figure 7) were created using climate data from the ERA5 project [13] for the ten years 2010-2019 as developed for the DEEP project and described in full elsewhere (see DEEP Project Report 6.01 [9]). WUFI Pro only considers 365 days in every year (i.e., it does not consider leap years) and so the RWD files were modified to remove any data for 29th February.

Figure 6: London RWD file - daily outdoor temperature, global horizontal radiation, and rainfall

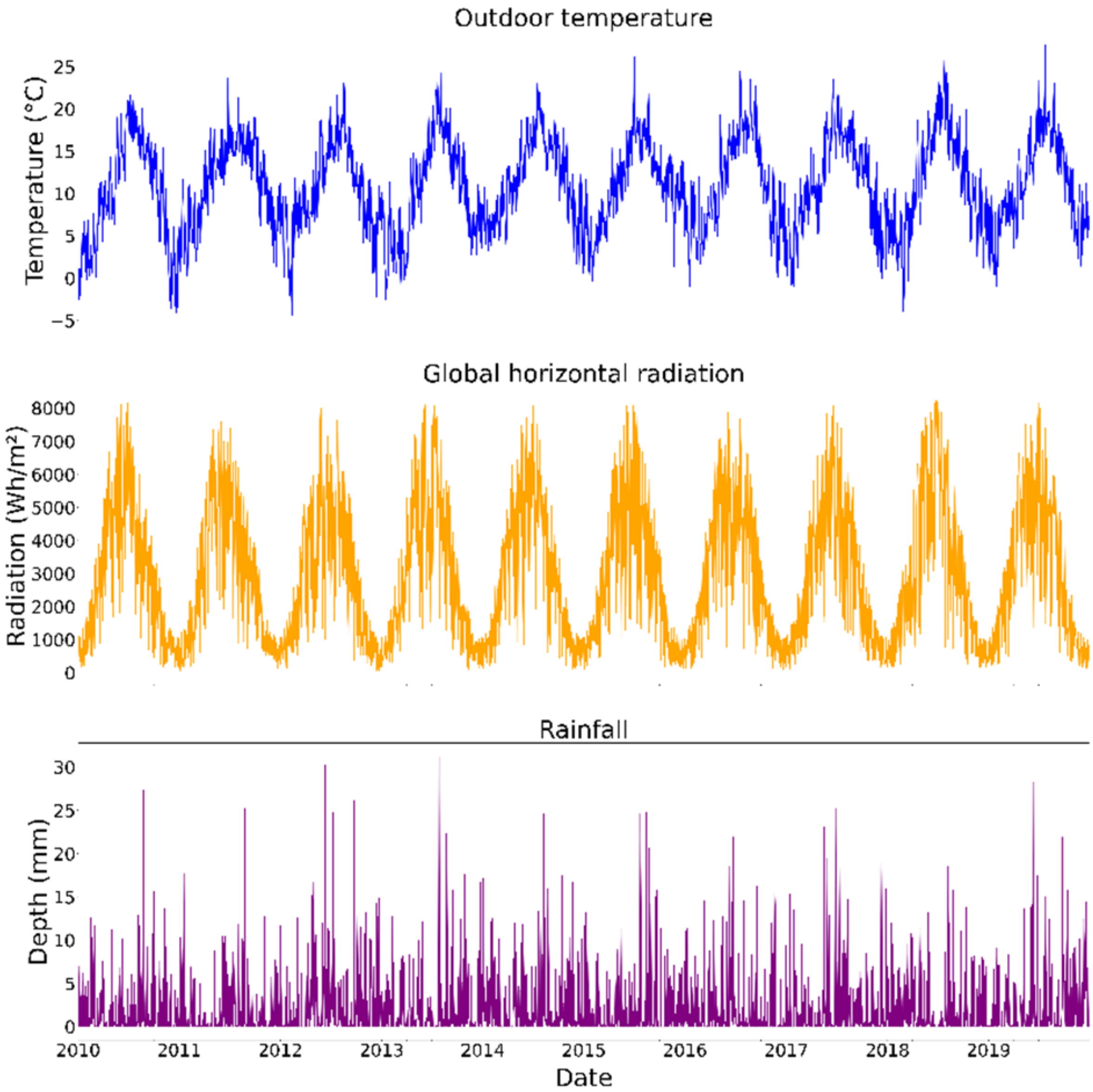
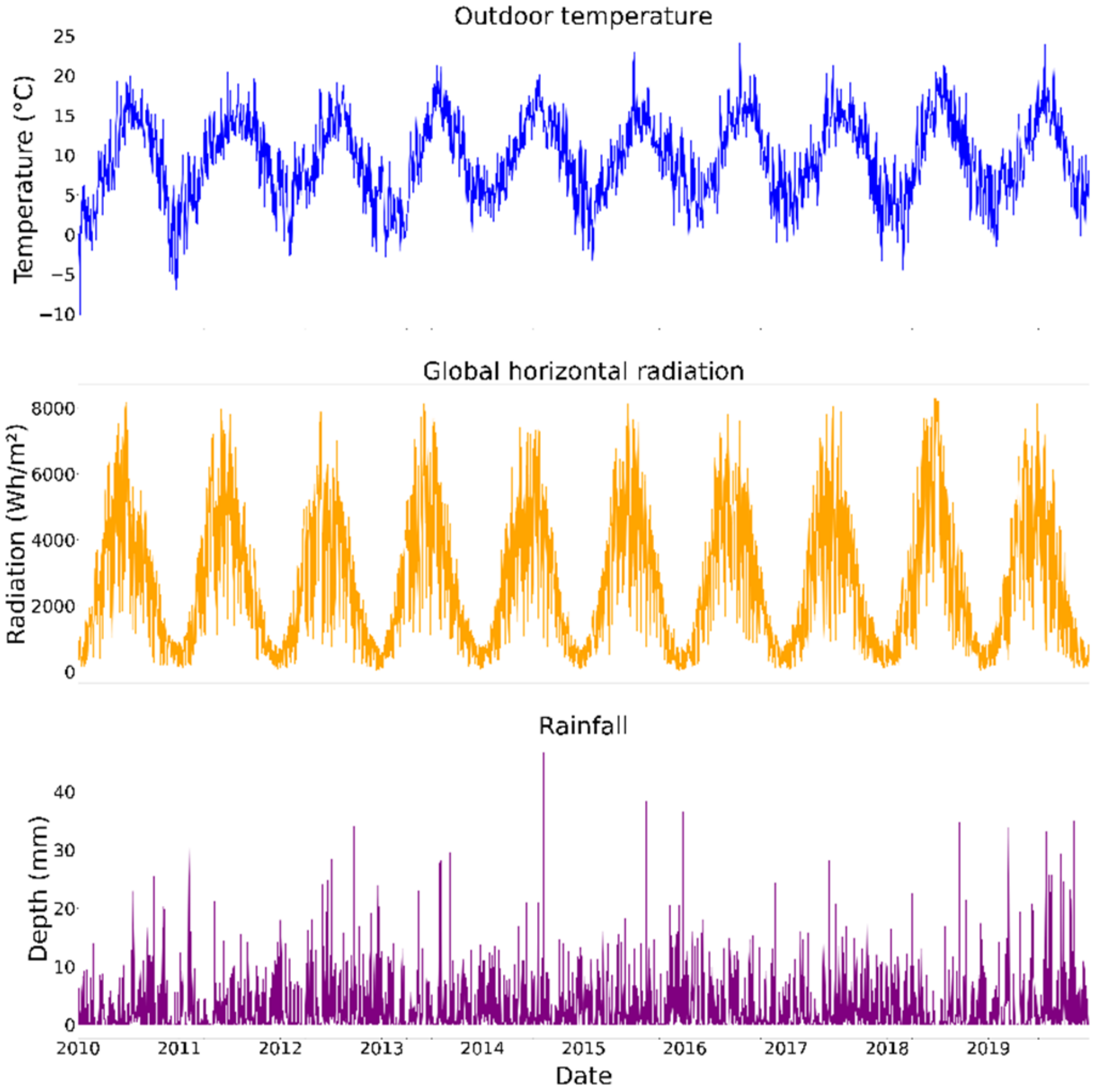


Figure 7: Daily outdoor temperature, global horizontal radiation, and rainfall in Manchester from the RWD file



Indoor temperature and relativity humidity were defined according to the relative model in EN 15026 [8] as implemented in WUFI Pro, assuming a medium moisture load as shown for London (Figure 8) and Manchester (Figure 9). The indoor temperature and humidity are correlated to the outdoor temperature, according to the medium moisture load:

- outdoor temperatures below 10°C
    - indoor temperature = 20°C
    - indoor RH = 30%
- outdoor temperatures between 10°C and 20°C
    - indoor temperature varies linearly between 20 and 25°C
    - indoor RH varies linearly between 30% and 60%
- outdoor temperatures greater than 20°C
    - indoor temperature = 25°C
    - indoor RH = 60%.

Figure 8: Indoor temperature and RH according to the EN 15026 model assuming a medium moisture load for 2010 (London RWD file)

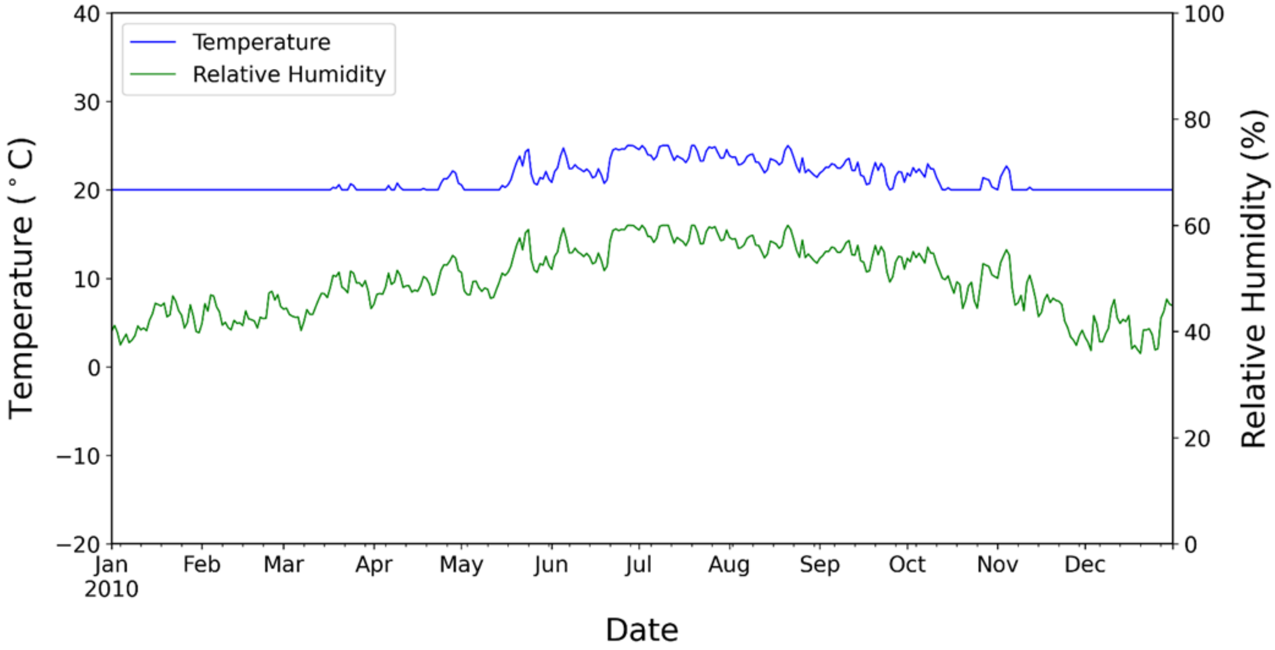
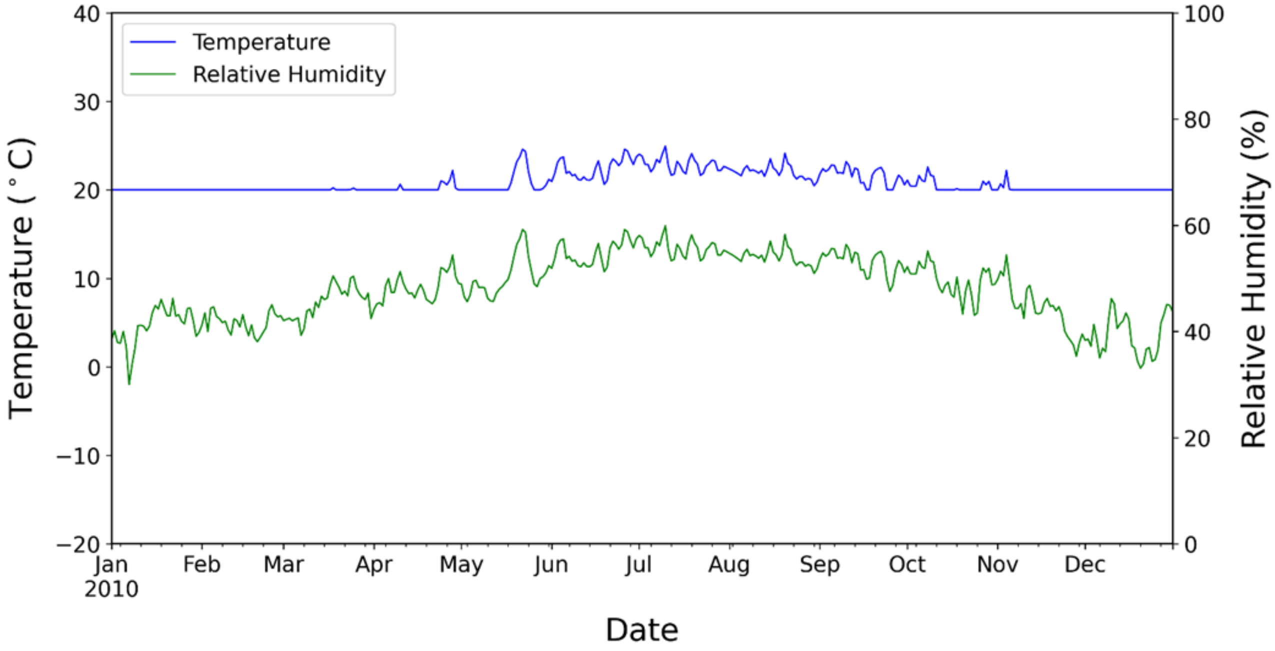
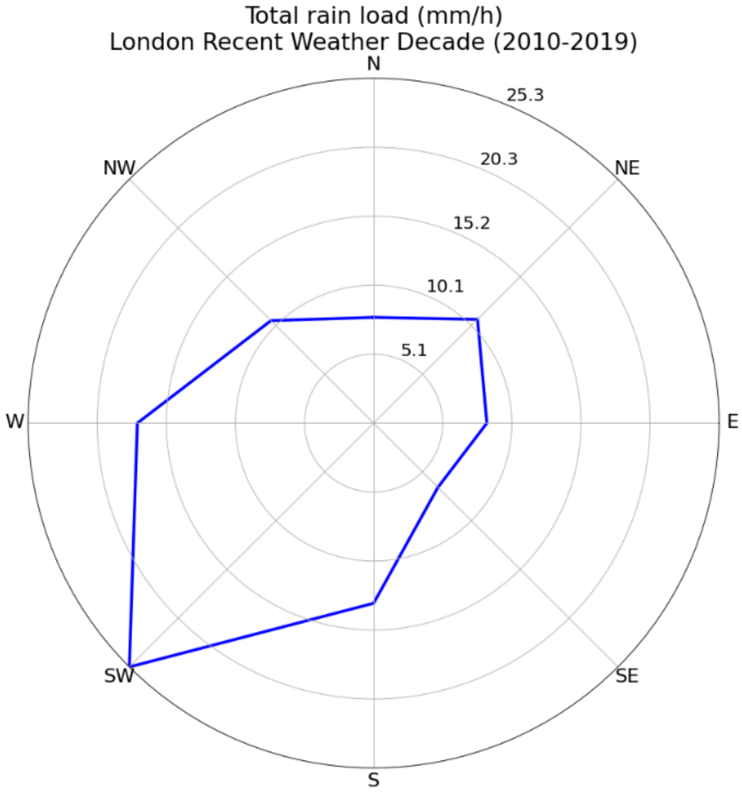


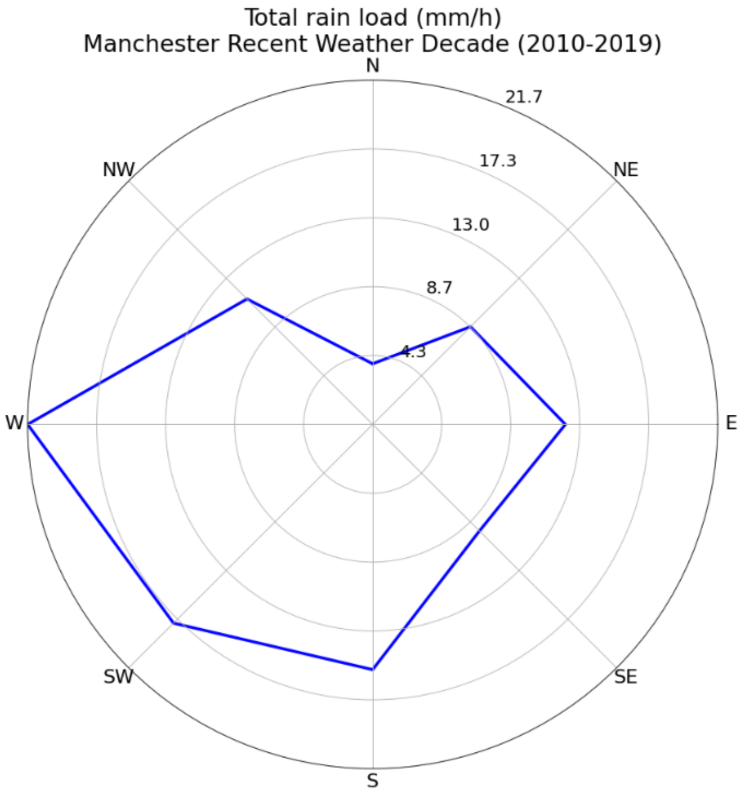
Figure 9: Indoor temperature and RH according to the EN 15026 model assuming a medium moisture load for 2010 (Manchester RWD file)



The walls were assessed in the orientation that gave the highest total wind driven rain load in the RWD: South-west for London and West for Manchester (Figure 10). All the material properties for the walls were extracted from the WUFI Pro database (Table 2).

Figure 10: Wind roses[9] depicting total rain load for London and Manchester RWD files





[9] The wind roses depict the distribution (as percentage of time) of wind direction in the eight principal orientations.

Table 2: Material property data for the walls

Material	Bulk density kg/m³	Porosity m³/m³	Specific Heat Capacity, Dry J/(kgK)	Thermal Conductivity, Dry, 10°C W/(mK)	Water Vapour Diffusion Resistance Factor	Free Water Saturation kg/m³	Water Absorption Coefficient kg/(m²s½)
Solid Brick ZC (medium absorptivity brick)	1985	0.28	836	0.908	23	188	0.183
Solid Brick ZQ (low absorptivity brick)	1972	0.26	800	0.904	30	108	0.0135
Solid Brick, extruded (high absorptivity brick)	1650	0.41	850	0.6	9.5	370	0.4
Solid Brick, hand-formed	1725	0.38	850	0.6	17	200	0.3
Solid Brick ZC – “brick cream”	1985	0.28	836	0.908	25.3	188	0.00915
Interior Plaster (Gypsum Plaster)	850	0.65	850	0.2	8.3	400	0.287
Gypsum board	850	0.65	850	0.2	8.3	400	0.287
Lime Plaster	1600	0.3	850	0.7	7	250	0.05
Air layer – 10 mm	1.3	0.999	1000	0.071	0.73	-	-
Air layer – 15 mm	1.3	0.999	1000	0.0953	0.62	-	-
Wood-fibre insulation board	155	0.981	1400	0.042	3	980	0.007
EPS	15	0.95	1500	0.04	30	-	-
AVCL (polyethylene)-membrane	130	0.001	2300	2.3	50000	-	-

For the simulation, the ‘Automatic (II) grid generator’ in WUFI Pro was used, and the number of grid elements was set to 250. ‘Adaptive timestep control’ was activated using 3 steps and 5 maximum stages (the default option) to eliminate possible convergence errors. Default values in WUFI Pro were selected for the surface thermal resistances (0.0588 (m^2K)/W for the exterior wall surface and 0.125 (m^2K)/W for the interior). Default values were also selected for the ground reflectivity (0.2) and the adhering fraction of rain (0.7).

To set the starting moisture content of each wall, the uninsulated walls were simulated for five years[10] using a custom weather file generated with data for 2009 in each location. The

[10] Five years was enough time for the models to achieve convergence.

moisture content of each layer of the wall at the end of this period was then used as the initial moisture content. Results were then generated by simulating the walls for 40 years, repeating the RWD file four times to ensure that a dynamic equilibrium was achieved, and the influence of initial moisture conditions removed. Only the final ten years were then used in the subsequent analysis and reporting.

5. Results

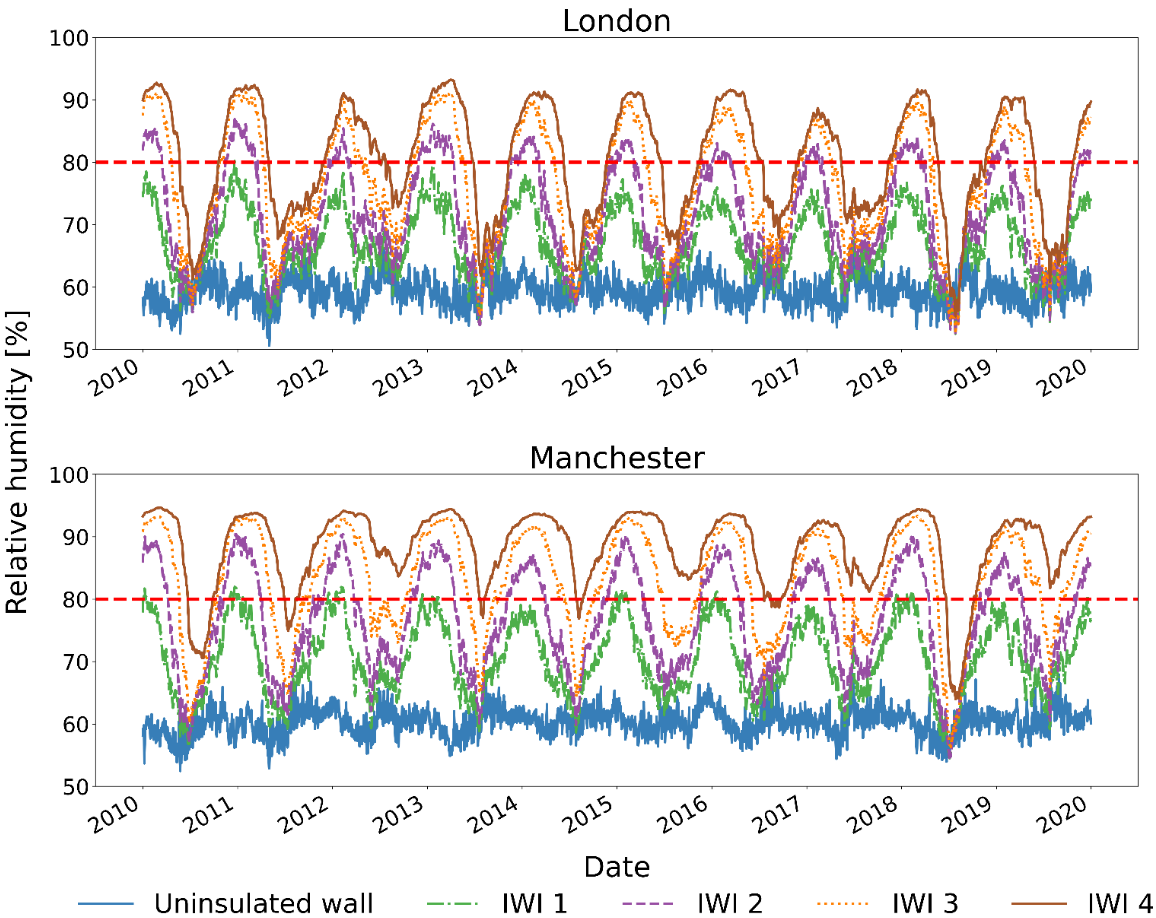
All results are given for the interface between brick and interior plaster in the uninsulated walls, and on the cold side of the insulation in the retrofitted ones. The results in this section all use the medium absorptivity brick described in Section 4. In all cases, the validity of the simulations was checked by ensuring no accumulation of water over time and no convergence errors were reported. The RH profiles for each wall case study in each location are considered (Section 5.1), the moisture risk RH.days are compared (Section 5.2), and the results of a parametric analysis are presented (Section 5.3).

5.1 Simulated RH profiles

5.1.1 IWI A – Wood-fibre

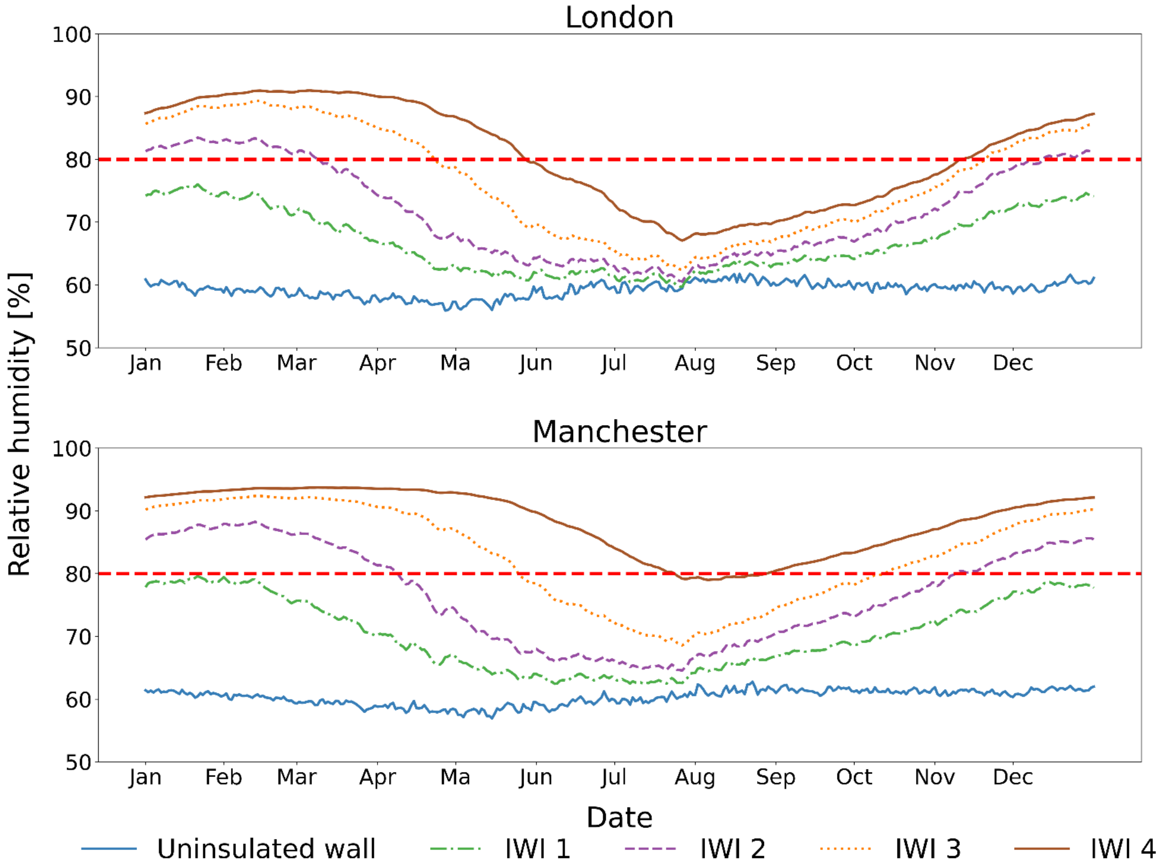
The 10-year RH profiles for the uninsulated wall and four thicknesses of wood-fibre IWI for London and Manchester (Figure 11) show a repeating annual cycle. In each year, the RH increases over winter and then decreases through the summer. This variation is due to the temperature of the wall and wetting that occurs (mainly) from wind driven rain.

Figure 11: Mean daily RH for the uninsulated wall and four thicknesses of IWI A (wood-fibre), simulated with the London (upper) and Manchester (lower) RWD file



As insulation thickness increases, from IWI 1 to IWI 4 (as described in Table 1 of Section 3), the average daily RH (averaged over the 10 years of the RWD) is higher on every day of the year (Figure 12). Therefore, insulation leads to increased RH and the thicker the insulation (lower the U-value) the higher the RH.

Figure 12: Mean daily RH averaged over all years in the RWD for the uninsulated wall and four thicknesses of IWI A (wood-fibre), simulated with the London (upper) and Manchester (lower) RWD file

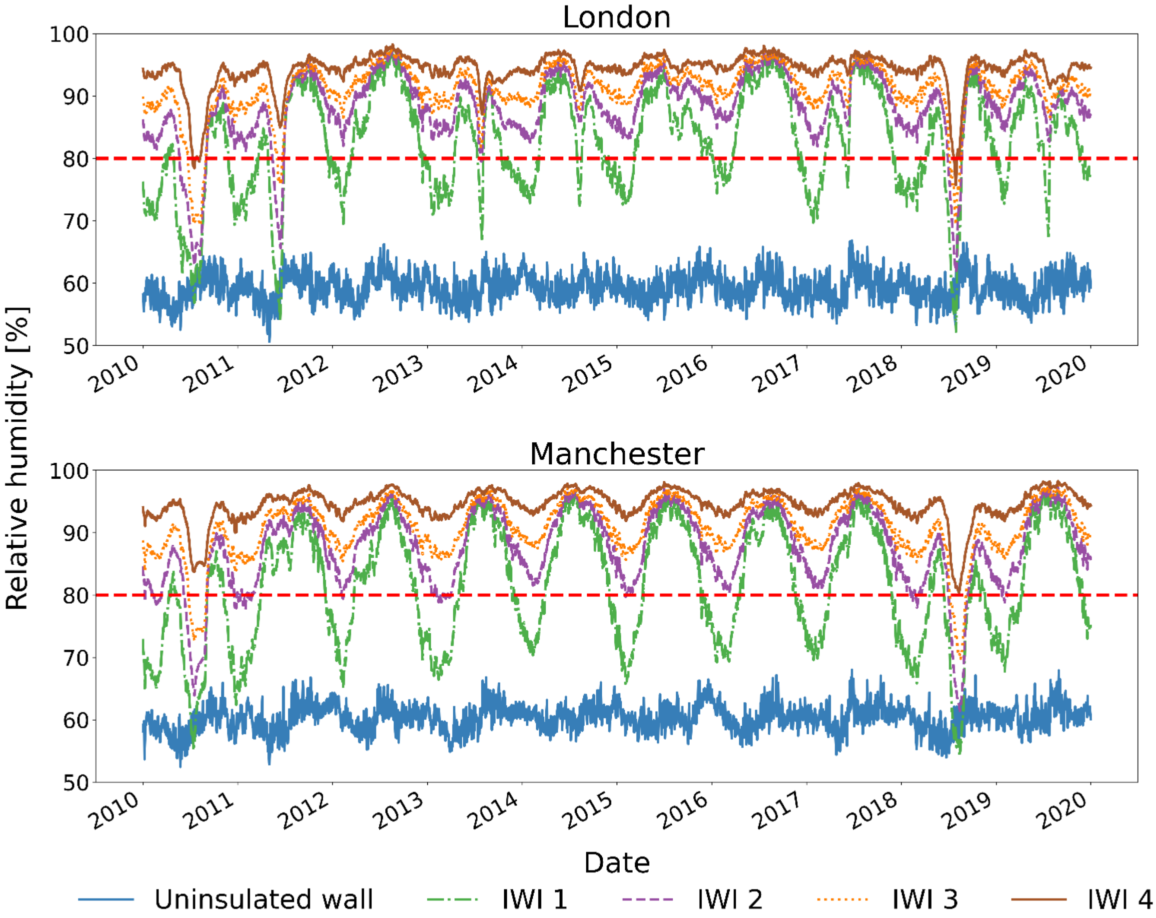


The uninsulated wall and the wall with IWI 1 (target U-value = 1.1 W/(m^2·K)) do not experience daily average RH levels above 80% in either London or Manchester, whereas those with more insulation do (Figure 12). The insulated wall, IWI4 (target U-value = 0.3 W/(m^2·K)) does not have RH levels less than 80% for very many days of the year in the Manchester case where wind driven rain exposure is higher.

5.1.2 IWI B - EPS with AVCL

The 10-year RH profiles for the uninsulated wall and four thicknesses of EPS with AVCL IWI for London and Manchester (Figure 13) show a repeating annual cycle, but with higher RH than for wood-fibre IWI.

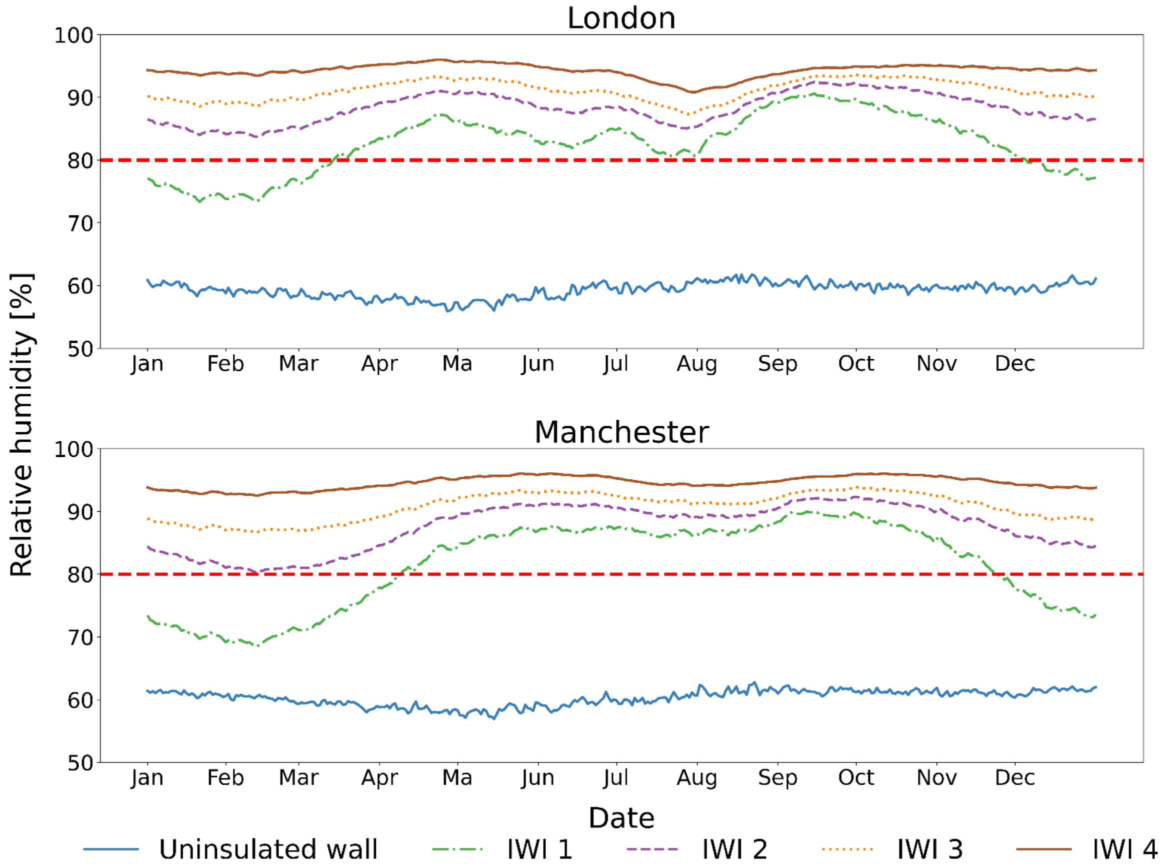
Figure 13: Mean daily RH for the uninsulated wall and four thicknesses of IWI B (EPS with AVCL), simulated with the London (upper) and Manchester (lower) RWD file



As insulation thickness increases, from IWI 1 to IWI 4, the average daily RH is higher on every day of the year (Figure 14) and only the uninsulated wall does not experience daily average RH levels above 80% in either London or Manchester.

RH does not decline during the summer period, in the same way as it does for the wood-fibre IWI but is at a minimum in February (Figure 14). This February minimum is higher than the summertime minimum for the equivalent wood-fibre IWI.

Figure 14: Mean daily RH averaged over all years in the RWD for the uninsulated wall and four thicknesses of IWI B (EPS with AVCL), simulated with the London (upper) and Manchester (lower) RWD file

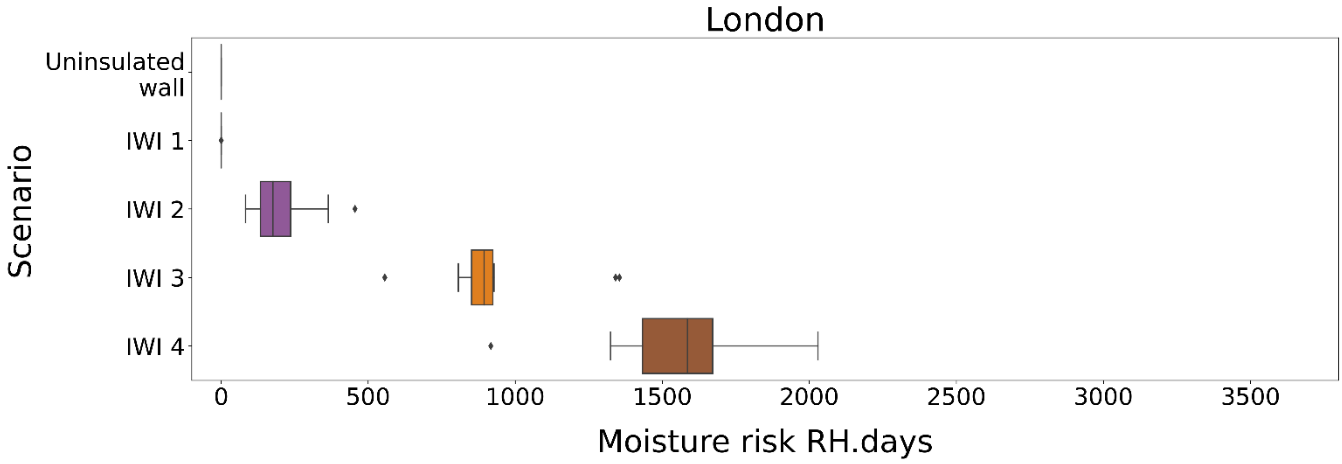


5.2 Moisture risk RH.days

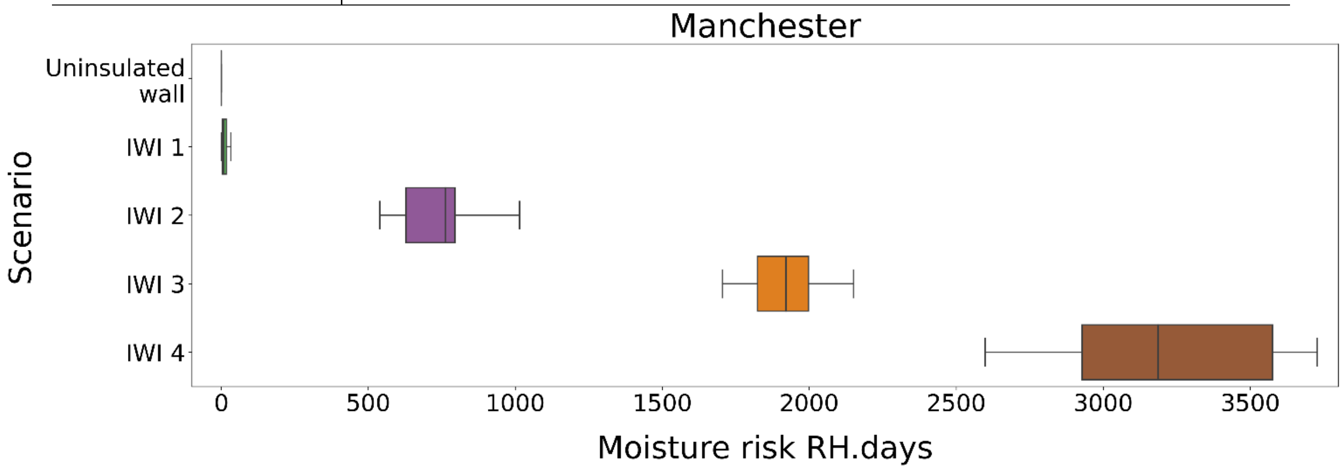
The RH profiles presented in Section 5.1 show that the moisture risk will increase with insulation thickness and that moisture risk is higher with IWI B – EPS with AVCL, than it is with IWI A - wood-fibre. In this section, the new metric of moisture risk RH.days is used to quantify the differences. Moisture risk RH.days in each of the ten years of the RWD files for London and Manchester are shown as a box plot which displays the median, the lower and upper quartiles, the interquartile range and the whiskers that show the rest of the data; extreme values are shown as outliers. In addition, the number of the annual moisture risk RH.days for each case is shown in the table below each plot.

For IWI A – wood-fibre, the moisture risk RH.days are shown in Figure 15. For both London and Manchester, there are zero moisture risk RH.days for the uninsulated wall. For IWI 1 (target U-value of 1.1 W/(m^2·K)), there are only 0.2 moisture risk RH.days that occur for one year (2010) of the London RWD. For the Manchester RWD, IWI 1 results in a very small number of moisture risk RH.days in every year. In both London and Manchester, the average number of moisture risk RH.days (as seen in the tables of Figure 15) increases as the insulation thickness increases from IWI 2 to IWI 4. The variance between years (as shown by the box plots in Figure 15) also increases with insulation thickness. This is a good demonstration of the benefit of such a metric applied over a decade of weather capturing the variability and its impacts.

Figure 15: Moisture risk RH.days for the uninsulated wall and four thicknesses of IWI A (wood-fibre), simulated with the London (upper) and Manchester (lower) RWD file



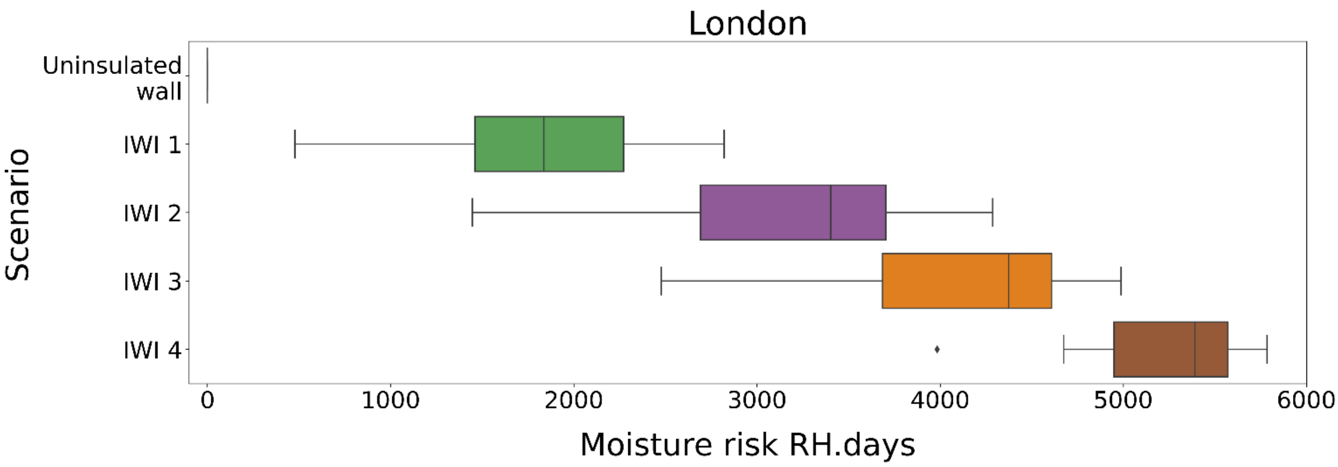
Scenario	**IWI A (wood-fibre) average moisture risk RH.days for London**									
(target U-value)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Uninsulated wall	0	0	0	0	0	0	0	0	0	0
IWI 1 (1.1 W/(m²·K))	0.2	0	0	0	0	0	0	0	0	0
IWI 2 (0.7 W/(m²·K))	455	254	172	365	183	147	83	90	180	129
IWI 3 (0.5 W/(m²·K))	1,355	913	807	1,342	876	866	847	557	911	928
IWI 4 (0.3 W/(m²·K))	1,932	1,325	1,575	2,030	1,597	1,542	1,681	917	1,396	1,644



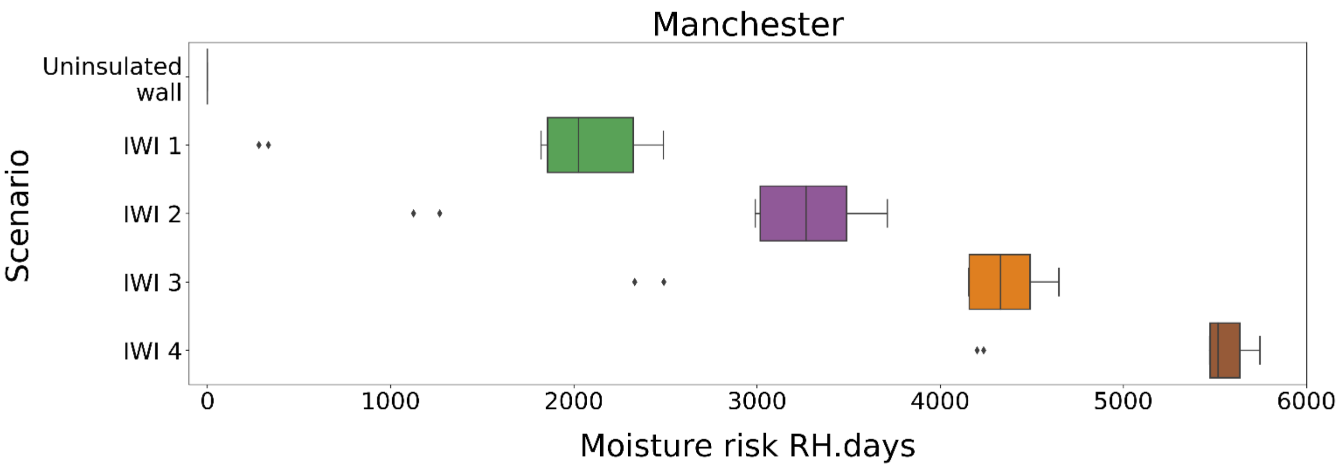
Scenario	**IWI A (wood-fibre) average moisture risk RH.days for Manchester**									
(target U-value)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Uninsulated wall	0	0	0	0	0	0	0	0	0	0
IWI 1 (1.1 W/(m²·K))	29	8	32	4	4	21	9	3	7	0.4
IWI 2 (0.7 W/(m²·K))	1,015	740	777	867	539	790	749	582	797	590
IWI 3 (0.5 W/(m²·K))	2,102	1,892	1,967	2,151	1,734	1,946	1,802	1,706	1,895	2,008
IWI 4 (0.3 W/(m²·K))	2,905	2,997	3,728	3,514	3,352	3,597	2,766	3,02	2,599	3,716

For IWI B – EPS with AVCL, the moisture risk RH.days are shown in Figure 16. The results are similar to those for IWI A. For both London and Manchester, there are zero moisture risk RH.days for the uninsulated wall. In both London and Manchester, the average number of moisture risk RH.days (as seen in the tables of Figure 16) increases as the insulation thickness increases from IWI 1 to IWI 4. The variance between years (as shown by the box plots in Figure 16) also increases with insulation thickness.

Figure 16: Moisture risk RH.days for the uninsulated wall and four thicknesses of IWI B (EPS with AVCL), simulated with the London (upper) and Manchester (lower) RWD file



Scenario (target U-value)	IWI A (wood-fibre) average moisture risk RH.days for London									
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Uninsulated wall	0	0	0	0	0	0	0	0	0	0
IWI 1 (1.1 W/(m²·K))	477	1,784	2,697	951	1,889	2,045	2,821	2,348	1,401	1,641
IWI 2 (0.7 W/(m²·K))	1,446	2,782	4,102	2,547	3,422	3,708	4,287	3,689	2,663	3,387
IWI 3 (0.5 W/(m²·K))	2,478	3,661	4,862	3,759	4,477	4,617	4,988	4,586	3,550	4,272
IWI 4 (0.3 W/(m²·K))	3,984	4,928	5,758	5,010	5,454	5,552	5,786	5,578	4,675	5,328



Scenario (target U-value)	IWI A (wood-fibre) average moisture risk RH.days for Manchester									
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Uninsulated wall	0	0	0	0	0	0	0	0	0	0
IWI 1 (1.1 W/(m²·K))	281	1,964	1,822	2,019	2,482	2,351	2,033	2,247	333	2,490
IWI 2 (0.7 W/(m²·K))	1,126	3,098	3,234	2,991	3,712	3,499	3,303	3,461	1,269	3,583
IWI 3 (0.5 W/(m²·K))	2,333	4,168	4,289	4,157	4,648	4,499	4,373	4,472	2,492	4,577
IWI 4 (0.3 W/(m²·K))	4,238	5,483	5,531	5,471	5,724	5,638	5,504	5,633	4,202	5,746

Comparing the results in Figure 15 and Figure 16, the moisture risk is higher for IWI B – EPS with AVCL than for the equivalent IWI A – wood-fibre. Overall, the results demonstrate the significant increase in moisture risk from adding IWI. The risk from EPS with AVCL is higher than that from an equivalent wood-fibre insulation. The year on year variation in moisture risk justifies the use of the RWD file.

5.3 Parametric analysis

A parametric analysis of the case study walls was carried out to understand how the relative moisture risk was affected by:

- Changing the insulation thickness and removing the AVCL from the EPS insulated wall.
- Changing the orientation of the wall.
- Changing the indoor moisture load.
- Changing the thermo-physical properties of the bricks.
- Waterproofing the outside surface of the wall using a “brick cream” coating.

5.3.1 Insulation thickness and AVCL

For each type of insulation, the thickness of insulation was varied from 10 mm to 150 mm in 20 mm increments. The indoor air temperature profiles and exterior wall characteristics in WUFI Pro were exported to EnergyPlus to predict the annual space heating demand[11] for the DEEP home 17BG House 17BG is a three-storey back-to-back end-terrace house built in 1890, with 65m^2 floor area. It has windows (which are double glazed) only on one façade, for more details about this house see the DEEP Methods 2.02 Report [14].

A third type of insulation was introduced: IWI C – EPS without AVCL. IWI C was simply a version of IWI B, but without the AVCL layer. This was modelled to explore further the difference between vapour open and vapour closed solutions.

The results from using the London RWD file (Figure 17) have a similar pattern to those from using the Manchester RWD file (Figure 18). In all cases, the light blue shaded area represents the range of annual results from the ten years of weather. The relative moisture risk (RH.days) is higher in all cases for the Manchester weather, as would be expected due to the higher wind-driven rain load. Wood-fibre insulation (IWI A) reduces the moisture risk when compared with the EPS insulation (IWI B). Removing the AVCL layer of the EPS insulation (IWI C) reduces the moisture risk to some extent. This suggests that the wood-fibre insulation and the EPS without AVCL are drying to the inside of the home i.e., a significant proportion of the moisture is moving through the wall and into the room where it will be ventilated away. The

[11] The indoor air temperature profiles in WUFI Pro were used as set-point temperatures and with the aid of an ideal loads system, heat was added or extracted to maintain these temperatures.

AVCL layer is designed to stop moisture from the room entering the wall but this will also reduce the ability of the wall to dry to the room.

Figure 17: The impact of insulation thickness (U-value) on moisture risk RH.days and space heating energy demand for IWI A-C simulated with the London RWD file

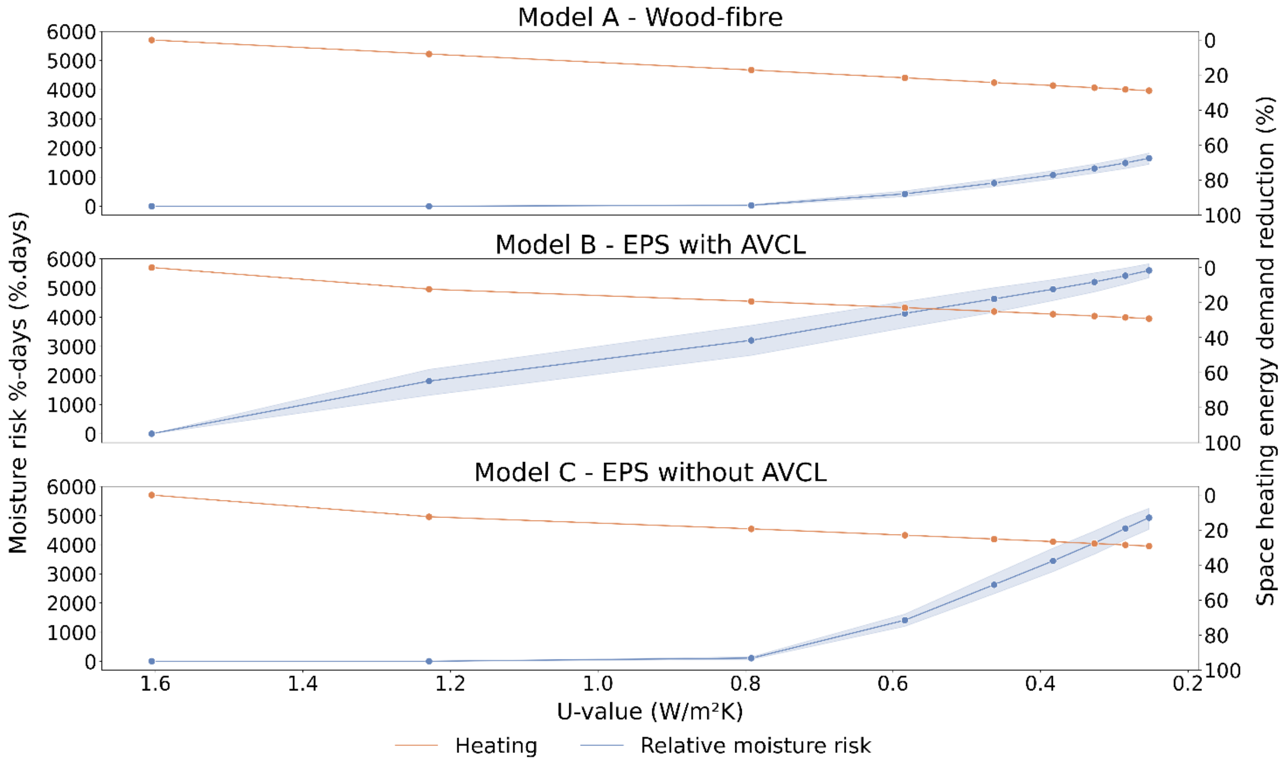
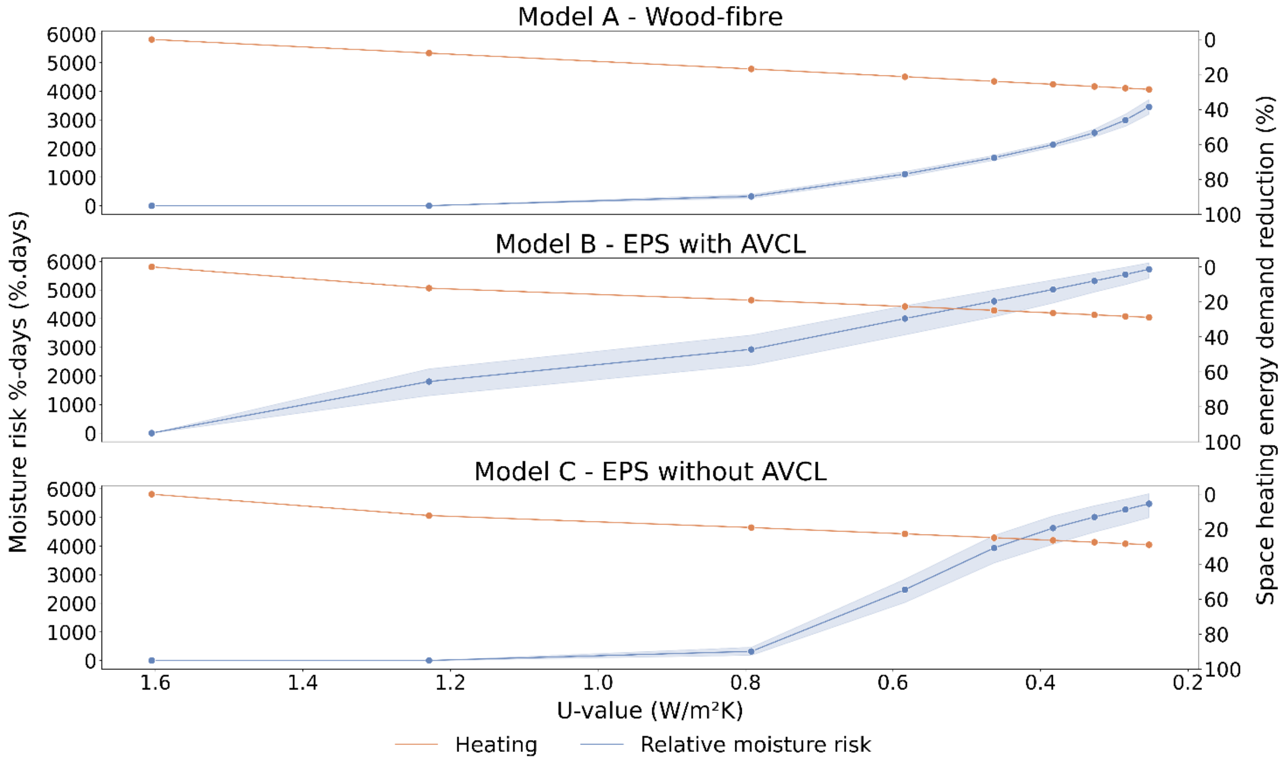


Figure 18: The impact of insulation thickness (U-value) on moisture risk RH.days and space heating energy demand for IWI A-C simulated with the Manchester RWD file



For IWI A - wood-fibre, moisture risk RH.days are relatively low until U-value is reduced to about 0.8 W/(m^2·K) when the moisture risk increases sharply (Figure 17 and Figure 18). A U-value of 0.8 W/(m^2·K) will reduce heating demand by about 20% in London and in Manchester compared to the maximum reduction of about 30% when U-values are reduced to 0.3 W/(m^2·K), for the case-study building modelled here. This suggests that there is potential for thinner IWI to deliver energy savings without significantly increasing moisture risk.

5.3.2 Orientation

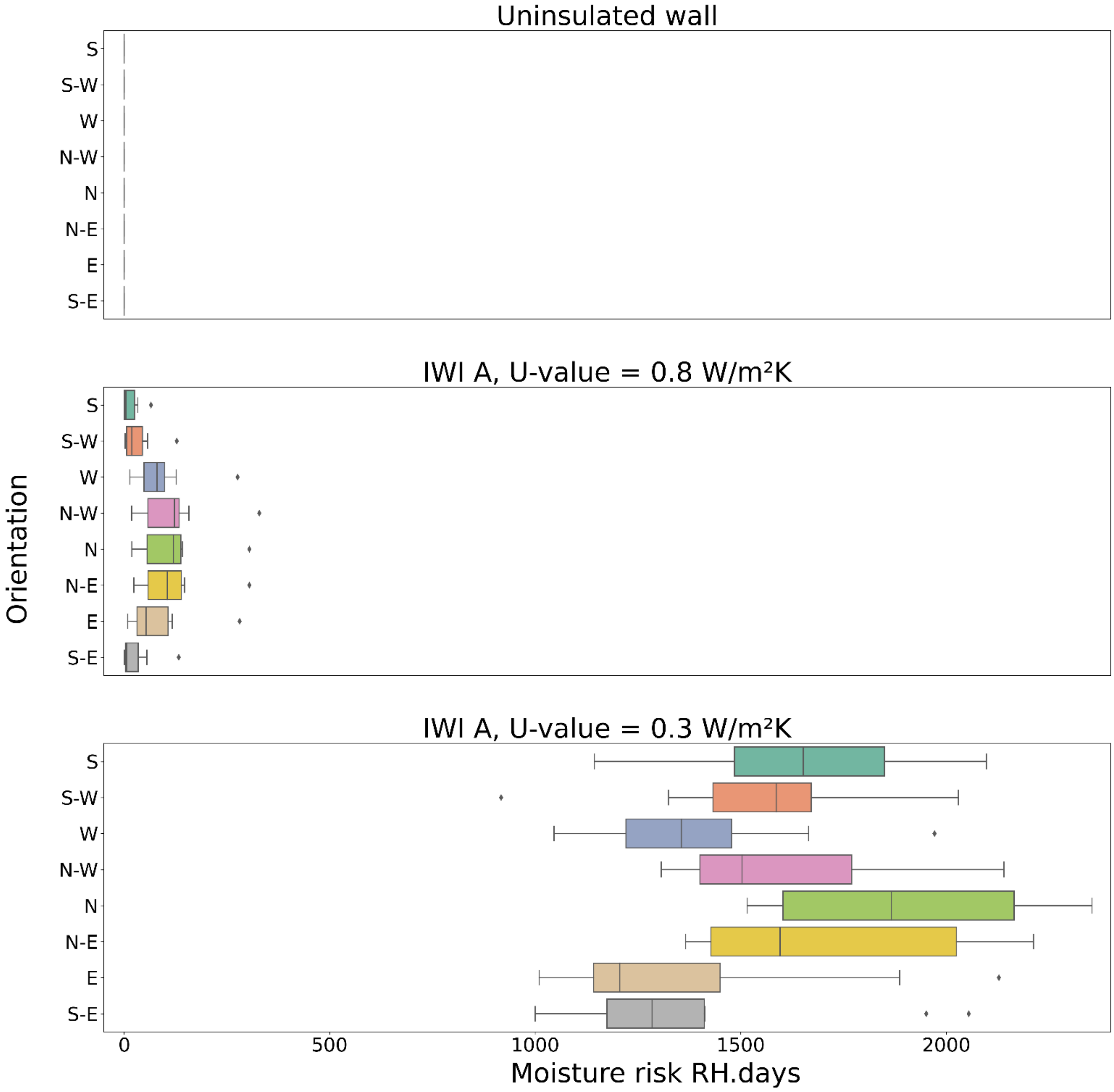
The IWI A – wood-fibre insulation wall was modelled in eight principal orientations (South, South-West, West, North-West, North, North-East, East, South-East) and in three cases:

1. Without insulation
2. With a U-value equal to 0.8 W/(m^2·K)
3. With a U-value equal to 0.3 W/(m^2·K)

IWI A was chosen as it had a lower relative moisture risk than IWI B (see Section 5.2). The U-value of 0.8 W/(m^2·K) was chosen because this was a threshold above which moisture risk rose sharply (see Section 5.3.1). The U-value of 0.3 W/(m^2·K) was chosen because this is the target value for renovated walls according to the building regulations.

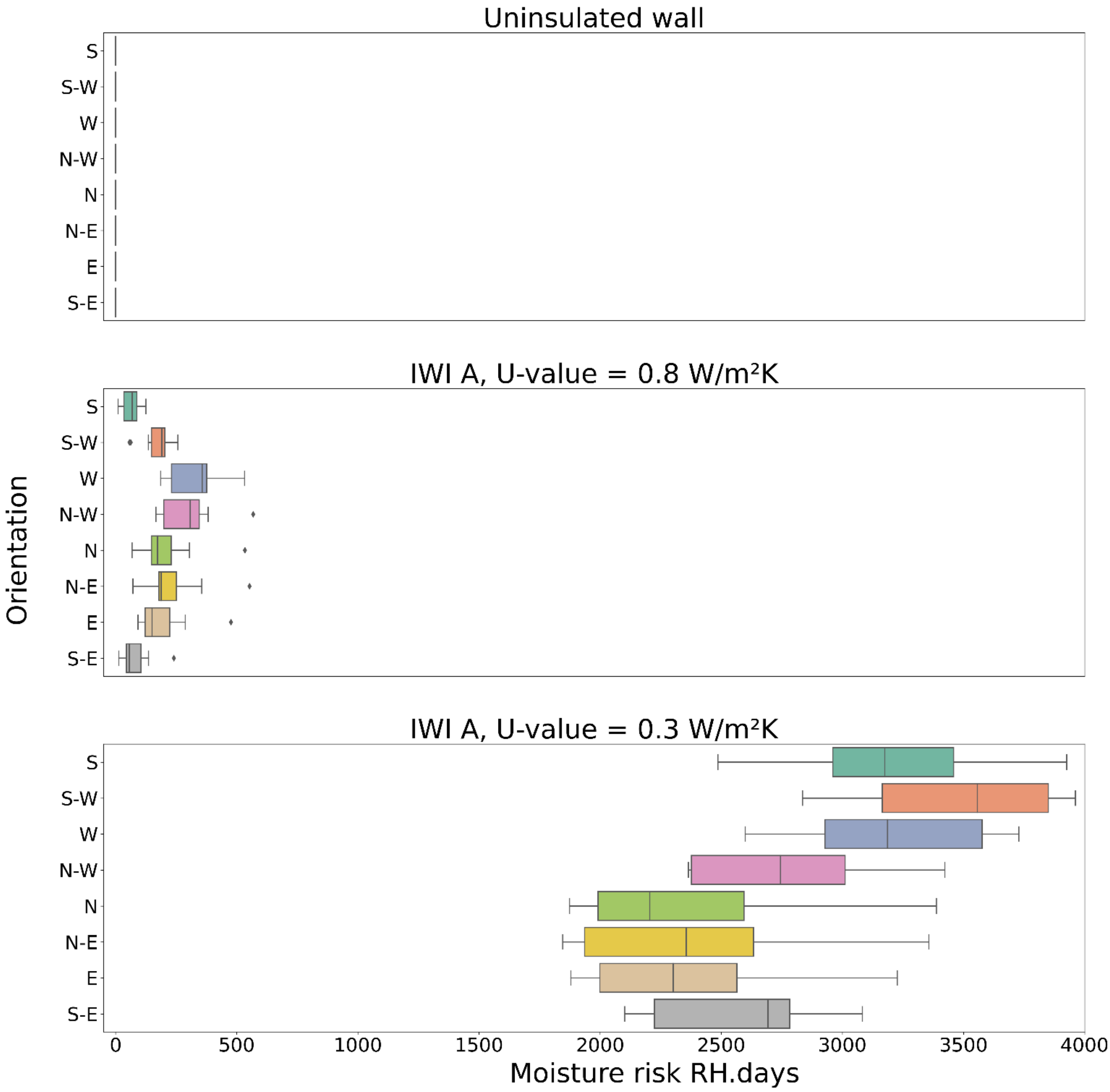
The relative moisture risk in each of the ten years of the RWD files for London, for each of the three U-value cases in each orientation, is shown in Figure 19. The relative moisture risk is zero for the uninsulated wall regardless of orientation. For case 2 (U-value = 0.8 W/(m^2·K)), the average relative moisture risk varies from 15 RH.days (South orientation) to 118 RH.days (North-West orientation). For case 3 (U-value = 0.3 W/(m^2·K)), the average relative moisture risk varies from 1362 %.day (East orientation) to 1890 RH.days (North orientation).

Figure 19: Moisture risk RH.days in the uninsulated wall and two thicknesses of IWI A (wood-fibre), for eight different orientations, simulated with the London RWD file



The relative moisture risk in each of the ten years of the RWD files for Manchester, for each of the three U-value cases in each orientation, is shown in Figure 20. The relative moisture risk is zero for the uninsulated wall regardless of orientation. For case 2 (U-value = 0.8 W/(m^2·K)), the average relative moisture risk varies from 65 RH.days (South-East orientation) to 328 RH.days (West orientation). For case 3 (U-value = 0.3 W/(m^2·K)), the average relative moisture risk varies from 2359 RH.days (East orientation) to 3478 RH.days (South-West orientation).

Figure 20: Moisture risk RH.days in the uninsulated wall and two thicknesses of IWI A (wood-fibre), for eight different orientations, simulated with the Manchester RWD file



For both London and Manchester, the weather variability has a larger impact on the relative moisture risk than orientation. For London, it was the North-West and North orientations[12] that produced the highest relative moisture risk, rather than the South-West orientation that had the highest wind-driven rain load. It is hypothesised that this is due to reduced solar radiation on these walls leading to reduced drying at the external surface. For Manchester, the North-West and South-West orientations produced the highest relative moisture risk, and this aligns more closely with the West orientation that had the highest wind-driven rain load.

[12] For a U-value of 0.8 and 0.3 W/m^{2}K respectively.

In summary, orientation has an impact on the relative moisture risk but this is only noticeable at low U-values. For the uninsulated wall no moisture risk RH.days were recorded in all orientations for both locations. Relative moisture risk[13] in Manchester for the U-value of 0.8 $W/(m^2·K)$ (where a higher variability of relative moisture risk is recorded) varied from 65.1 RH.days (South orientation) to 328.4 RH.days (West orientation). This difference is equivalent to.3.6% of the maximum theoretical value of moisture risk RH.days. For the U-value of 0.3 $W/(m^2·K)$, relative moisture risk varied from 2358.8 RH.days (East orientation) to 3478.1 RH.days (South-West orientation). This difference is equivalent to.15.3% of the maximum theoretical value of moisture risk RH.days. Therefore, orientation needs to be considered when the U-value of the assessed building element drops below a value of 0.8 $W/(m^2·K)$.

5.3.3 Indoor moisture load

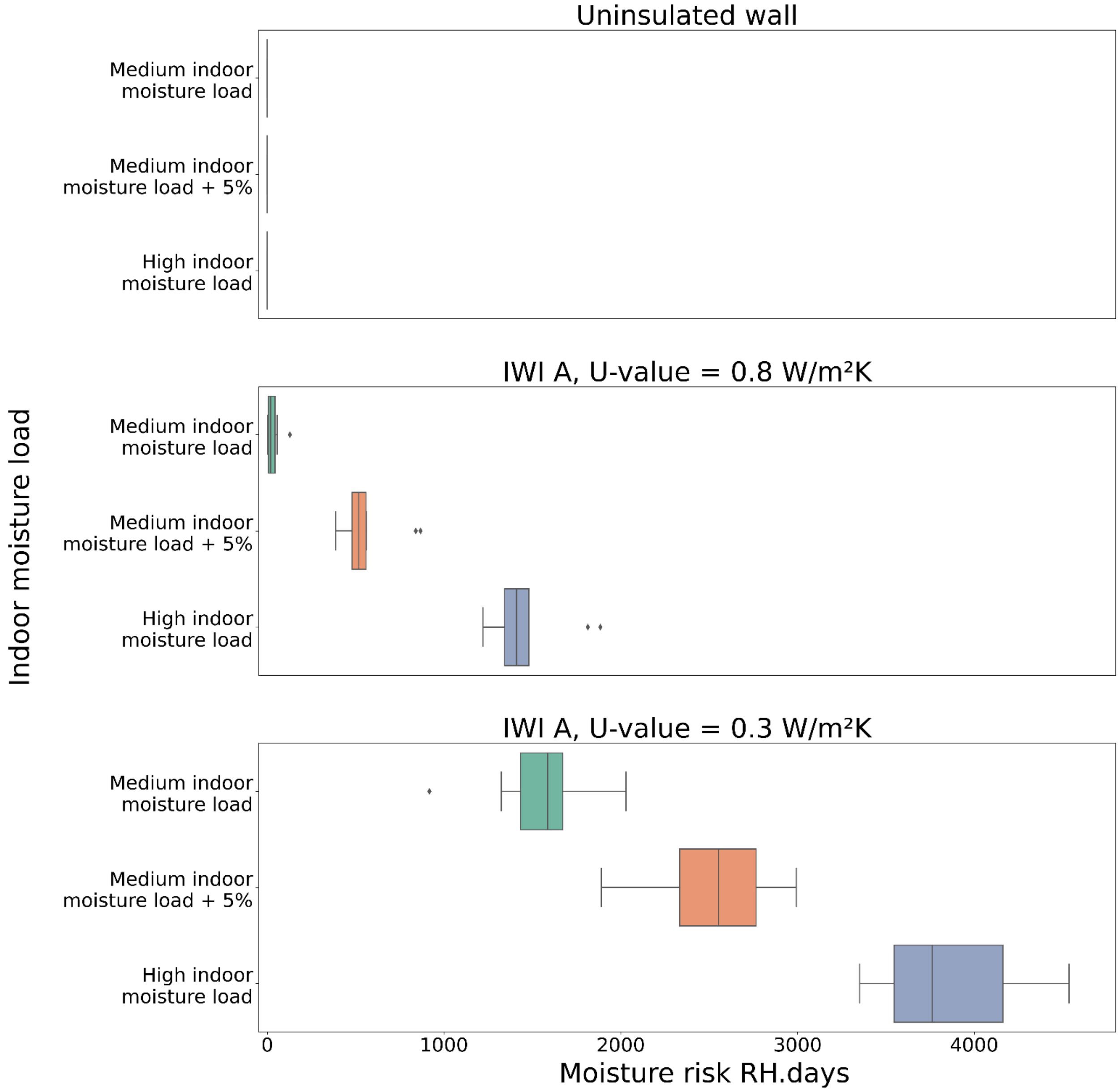
The three cases of the IWI A – wood-fibre insulation wall (without insulation; U-value = 0.8 $W/(m^2·K)$; and U-value = 0.3 $W/(m^2·K)$) were modelled with three different moisture loads, all according to the EN 15026 relative model (see Section 4):

1. Medium moisture load (as used in all previous analyses)
2. Medium moisture load +5% RH[14]
3. High moisture load (= medium moisture load + 10% RH)[15]

The relative moisture risk for the three cases, in each of the ten years of the RWD files for London, for each of the moisture loads, is shown in Figure 21. The relative moisture risk is zero for the uninsulated wall regardless of moisture load. For case 2 (U-value = 0.8 $W/(m^2·K)$), the average relative moisture risk increases from 32 RH.days (medium moisture load) to 1470 RH.days (high moisture load). For case 3 (U-value = 0.3 $W/(m^2·K)$), the average relative moisture risk increases from 1564 RH.days to 3855 RH.days.

[13] Averaged over the ten years.
[14] Minimum and maximum RH values of 30% and 60% increase to 35% and 65% respectively (see Section 4).
[15] Minimum and maximum RH values of 30% and 60% increase to 40% and 70% respectively (see Section 4).

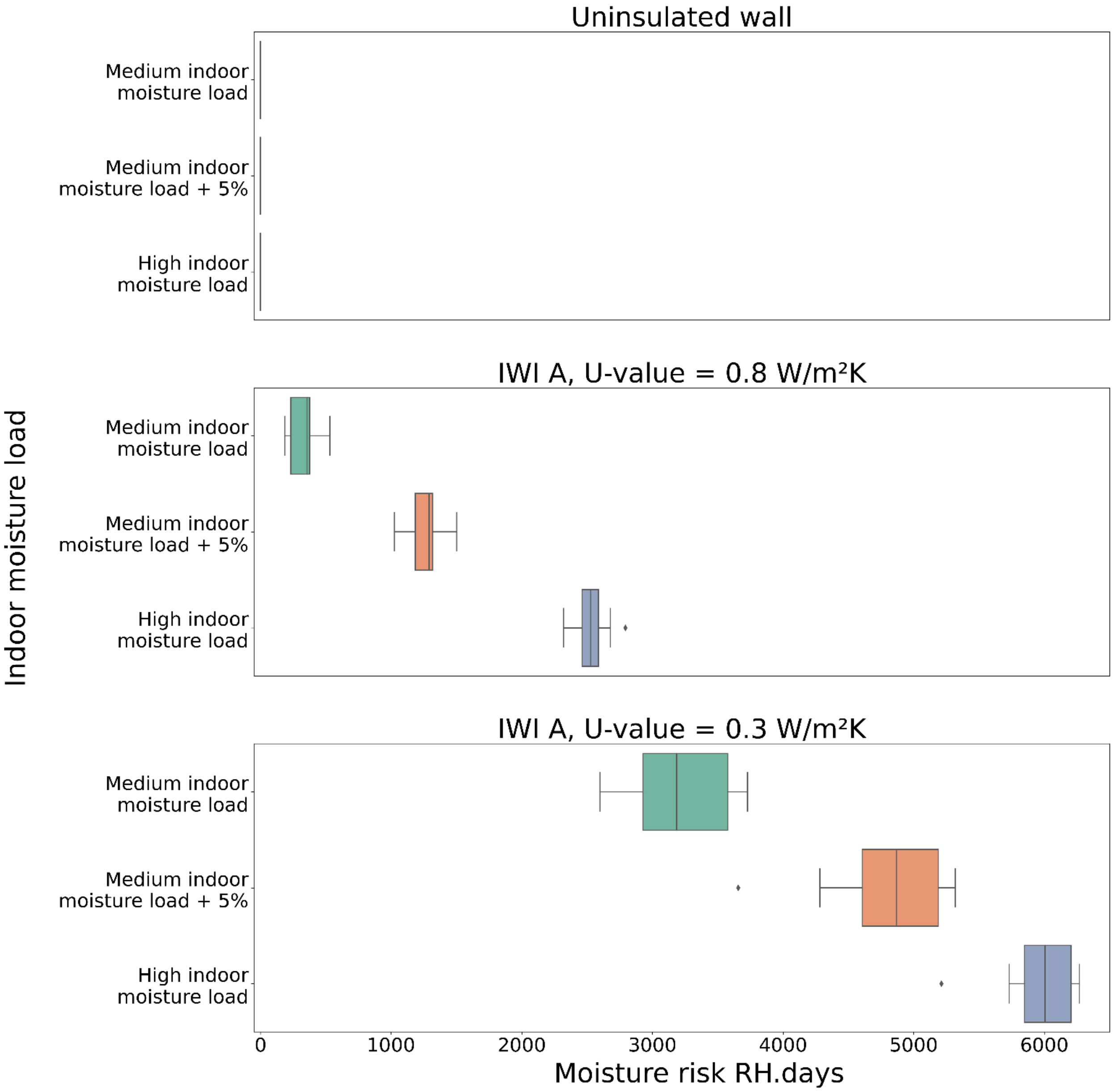
Figure 21: Moisture risk RH.days in the uninsulated wall and two thicknesses of IWI A (wood-fibre), for three different indoor moisture loads simulated with the London RWD file



The relative moisture risk for the three cases, in each of the ten years of the RWD files for Manchester, for each of the moisture loads, is shown in Figure 22. The relative moisture risk is zero for the uninsulated wall regardless of moisture load. For case 2 (U-value = 0.8 W/(m^2·K)), the average relative moisture risk increases from 328 RH.days (medium moisture load) to 2528 RH.days (high moisture load). For case 3 (U-value = 0.3 W/(m^2·K)), the average relative moisture risk increases from 3219 RH.days to 5959 RH.days.

These results show that the relative moisture risk is sensitive to the indoor moisture load chosen for the analysis. Homes with a higher moisture load will have a higher moisture risk. As it is not possible to know the moisture load in a home, and the absolute risk is less important in this *relative* assessment, the medium moisture load remains a sensible choice.

Figure 22: Moisture risk RH.days in the uninsulated wall and two thicknesses of IWI A (wood-fibre), for three different indoor moisture loads simulated with the Manchester RWD file



5.3.4 Brick properties

The three cases of the IWI A – wood-fibre insulation wall (without insulation; U-value = 0.8 W/(m^2·K); and U-value = 0.3 W/(m^2·K)) were modelled with four different bricks, taken from the WUFI Pro materials database:

1. Low water absorptivity
2. Medium water absorptivity (as used in all previous analyses)
3. High water absorptivity
4. "Solid Brick, hand-formed"

The hygrothermal properties of the bricks in a wall are known to affect moisture risk [6]. One important property is the water absorption coefficient (or A-value) which indicates how quickly a brick can absorb water. The three bricks of low, medium and high water absorptivity were chosen from statistical analysis of the WUFI Pro database (Table 3). To ensure the bricks were representative of UK solid wall construction, concrete, lime silica and insulated bricks were removed from the analysis, and only bricks with a thermal conductivity between 0.56 and 0.92 $W/(m^2K)$ were included[16]; this left eleven bricks for analysis as shown in Table 4.

Table 3: Statistical analysis of the hygrothermal properties of bricks in the WUFI Pro materials database (unusual brick types were removed).

Statistical measure	Density (kg/m^3)	Porosity (m^3/m^3)	Specific heat capacity (J/kgK)	Thermal conductivity (W/(m·K))	Vapour Diffusion Resistance Factor[-]	Water absorption coefficient ($kg/m^2s^{1/2}$)
Mean	1,824.6	0.32	857.4	0.70	16.5	0.187
Standard deviation	140.6	0.06	37.9	0.13	7.8	0.111
Minimum	1,642.0	0.24	800.0	0.58	7.0	0.014
25th percentile	1,731.0	0.27	837.5	0.60	10.0	0.108
50th percentile	1,807.0	0.32	850.0	0.64	13.0	0.183
75th percentile	1,936.0	0.36	880.0	0.76	23.0	0.255
Maximum	2,060.0	0.41	916.0	0.91	30.0	0.400

Table 4: Bricks from the WUFI Pro materials database that used in the selection of the bricks to be modelled in this report.

Source	Name
Fraunhofer_IBP	Solid_Brick_extruded_IBP
Fraunhofer_IBP	Solid_Brick_hand_formed
MASEA	Solid_Brick_ARB
MASEA	Solid_Brick_Bernhard
Fraunhofer_IBP	Solid_Brick_Masonry
MASEA	Solid_Brick_ZC
MASEA	Solid_Brick_ZE
MASEA	Solid_Brick_ZH
MASEA	Solid_Brick_ZK
MASEA	Solid_Brick_ZQ
MASEA	Solid_Brick_ZS

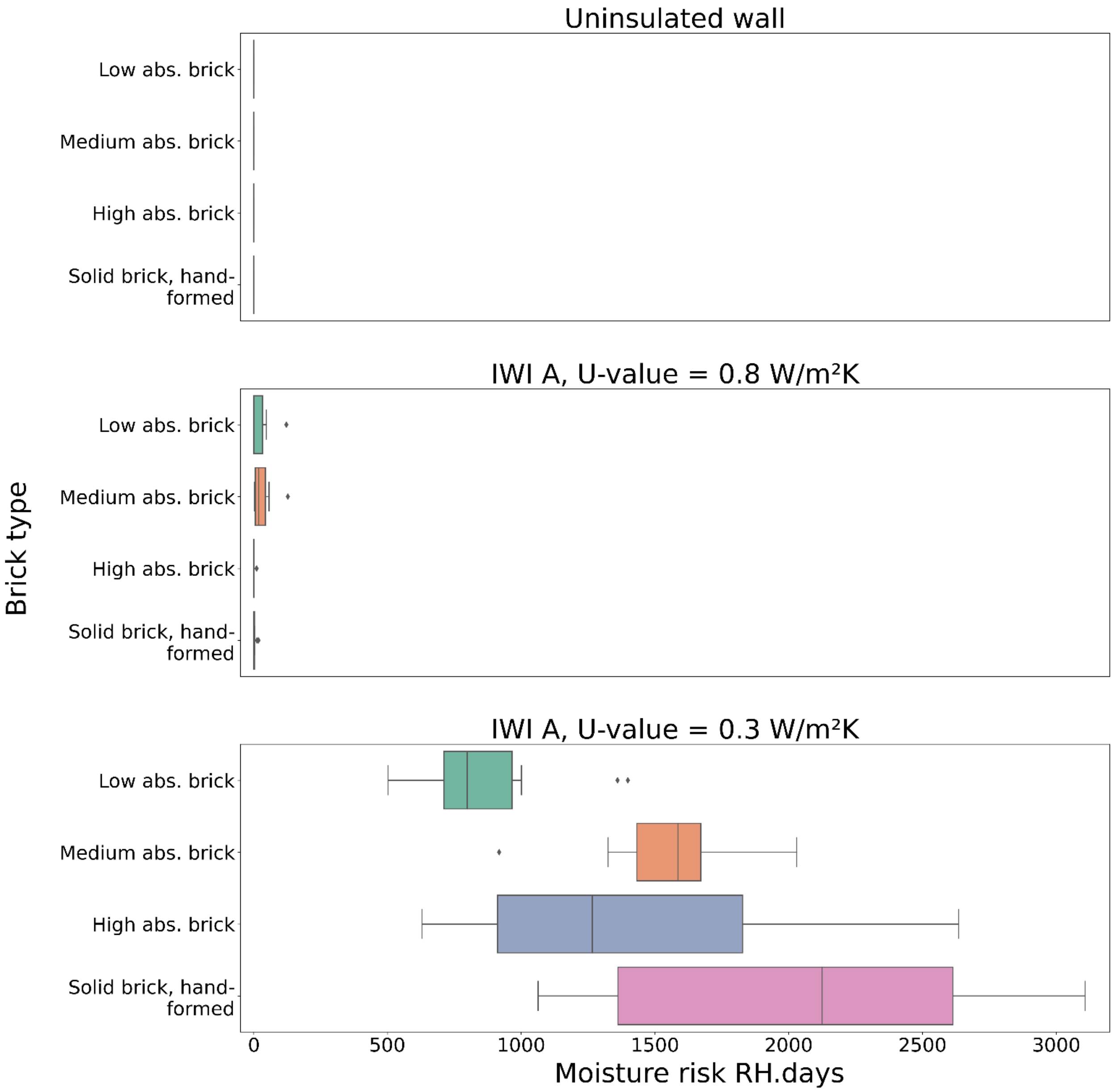
The low, medium and high absorptive bricks were those with the 5th, 50th and 95th percentile water absorption coefficient. These have a water absorption coefficient equal to 0.0097, 0.216 and 0.4 $kg/(m^2s^{1/2})$ respectively (see Table 2).

16 Bricks from a typical house monitored in the context of DEEP project have a conductivity equal to of 0.62 (inner brick) and 0.84 (outer brick) W/(m*K); a variation of ±10% in these figures was assumed in line with CIBSE AM11 guide.

The “Solid Brick, hand-formed” from the WUFI Pro database was also used. This was because this brick type was used in analysis by others [6] and has a similar water absorption coefficient (0.3 kg/($m^2s^{1/2}$) to a typical London Brick Fletton brick (0.32 kg/($m^2s^{1/2}$)) as tested by [15].

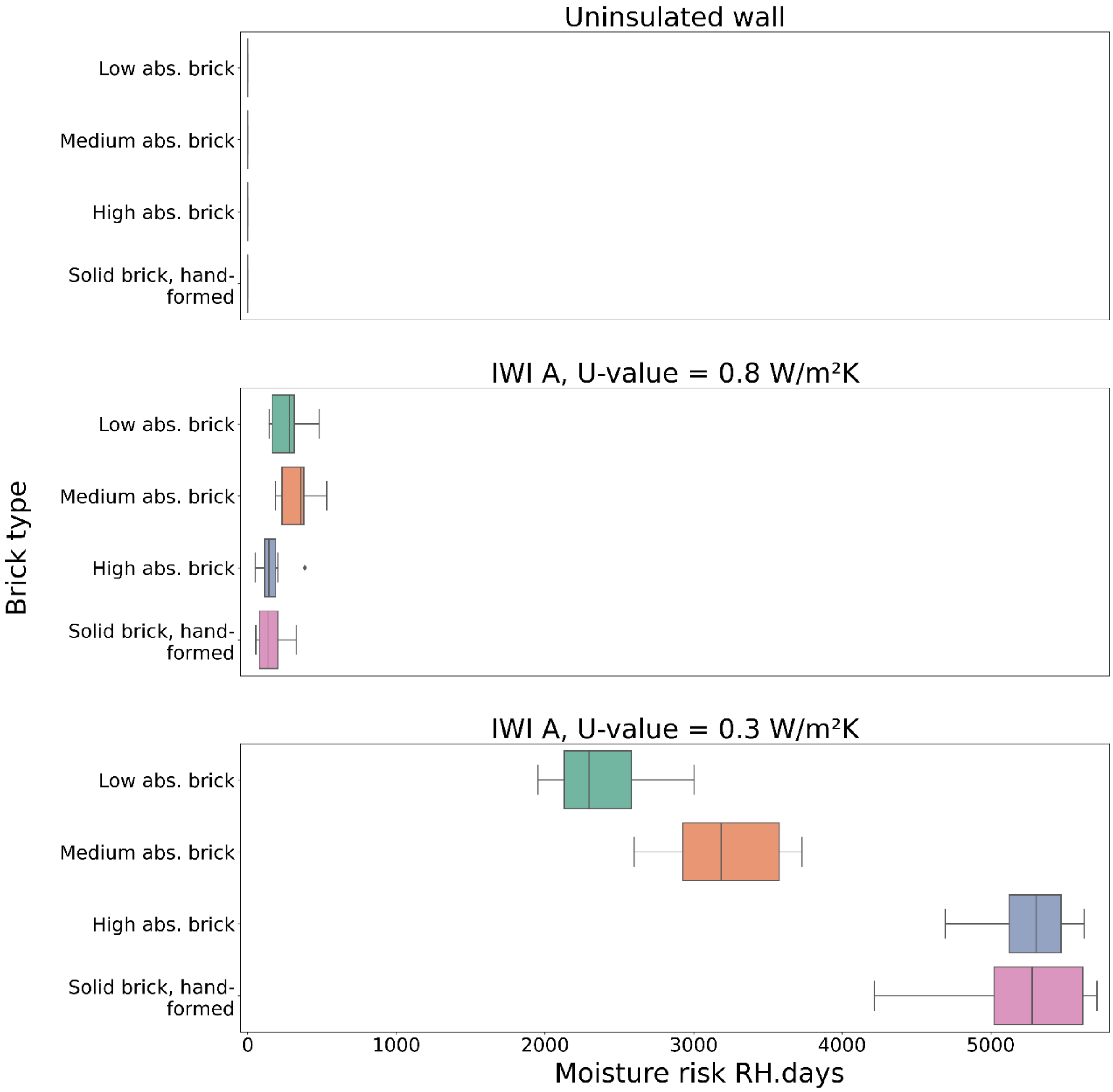
The relative moisture risk for the four cases, in each of the ten years of the RWD files for London, for each of the brick types, is shown in Figure 23. The relative moisture risk is zero for the uninsulated wall regardless of brick type. For case 2 (U-value = 0.8 W/(m^2·K)), the average relative moisture risk is marginally higher for the brick with low and medium water absorptivity than it is for the other two. For case 3 (U-value = 0.3 W/(m^2·K)), the average relative moisture risk varies from 879 RH.days (brick with low water absorptivity) to 2055 RH.days (Solid brick, hand-formed). The range of the relative moisture risk over the ten years (as shown by the box plots for each brick type) varies and there is no discernible pattern.

Figure 23: Moisture risk RH.days in the uninsulated wall and two thicknesses of IWI A (wood-fibre), for four different bricks simulated with the London RWD file



The relative moisture risk for the three cases, in each of the ten years of the RWD files for Manchester, for each of the brick types, is shown in Figure 24. The relative moisture risk is zero for the uninsulated wall regardless of brick type. For case 2 (U-value = 0.8 W/(m^2·K)), the average relative moisture risk is marginally higher for the brick with low and medium water absorptivity than it is for the other two. For case 3 (U-value = 0.3 W/(m^2·K)), the average relative moisture risk varies from 2378 RH.days (brick with low water absorptivity) to 5269 RH.days (brick with high water absorptivity). The range of the relative moisture risk over the ten years (as shown by the box plots for each brick type) varies and there is no discernible pattern.

Figure 24: Moisture risk RH.days in the uninsulated wall and two thicknesses of IWI A (wood-fibre), for four different bricks simulated with the Manchester RWD file



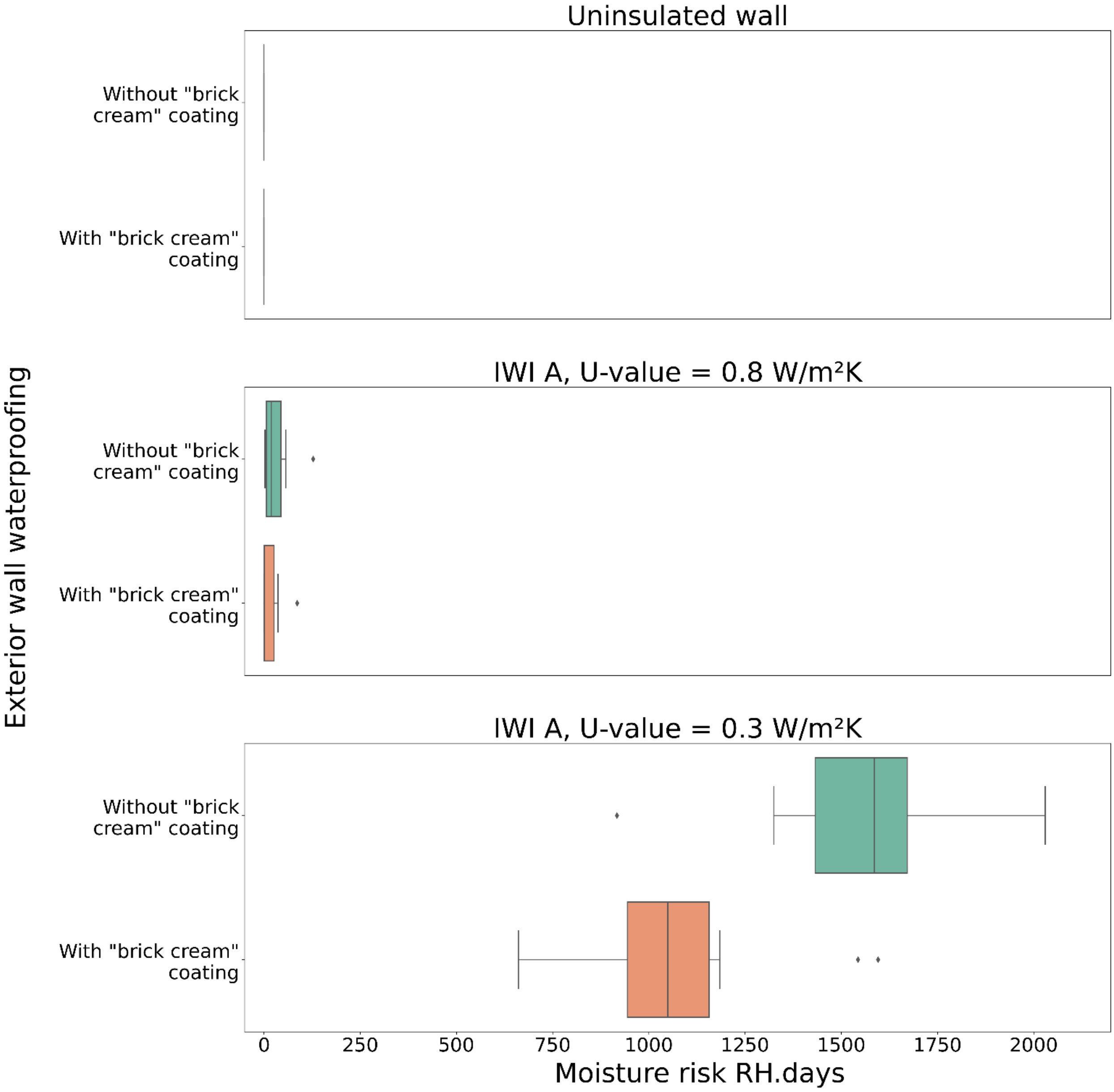
Overall, the water absorptivity of a brick is, on its own, not a good indicator of moisture risk. Bricks with higher water absorptivity can increase risk, as seen for the wall insulated to 0.3 W/(m^2·K). However, the moisture risk is relatively high regardless of the brick type.

5.3.5 Waterproofing exterior wall

The three cases of the IWI A – wood-fibre insulation wall (without insulation; U-value = 0.8 $W/(m^2{\cdot}K)$; and U-value = 0.3 $W/(m^2{\cdot}K)$) were modelled with a “brick cream” coating applied on the exterior side of the wall. These coatings are intended to reduce the moisture content of brick walls by resisting wind driven rain. It has been reported that the coating penetrates the first 10 mm of the brick, reducing the water absorption coefficient by 95% and increasing the water vapour diffusion resistance factor by 10% [6]. This was modelled as an additional brick layer with suitably modified properties (see Table 2 in Section 4).

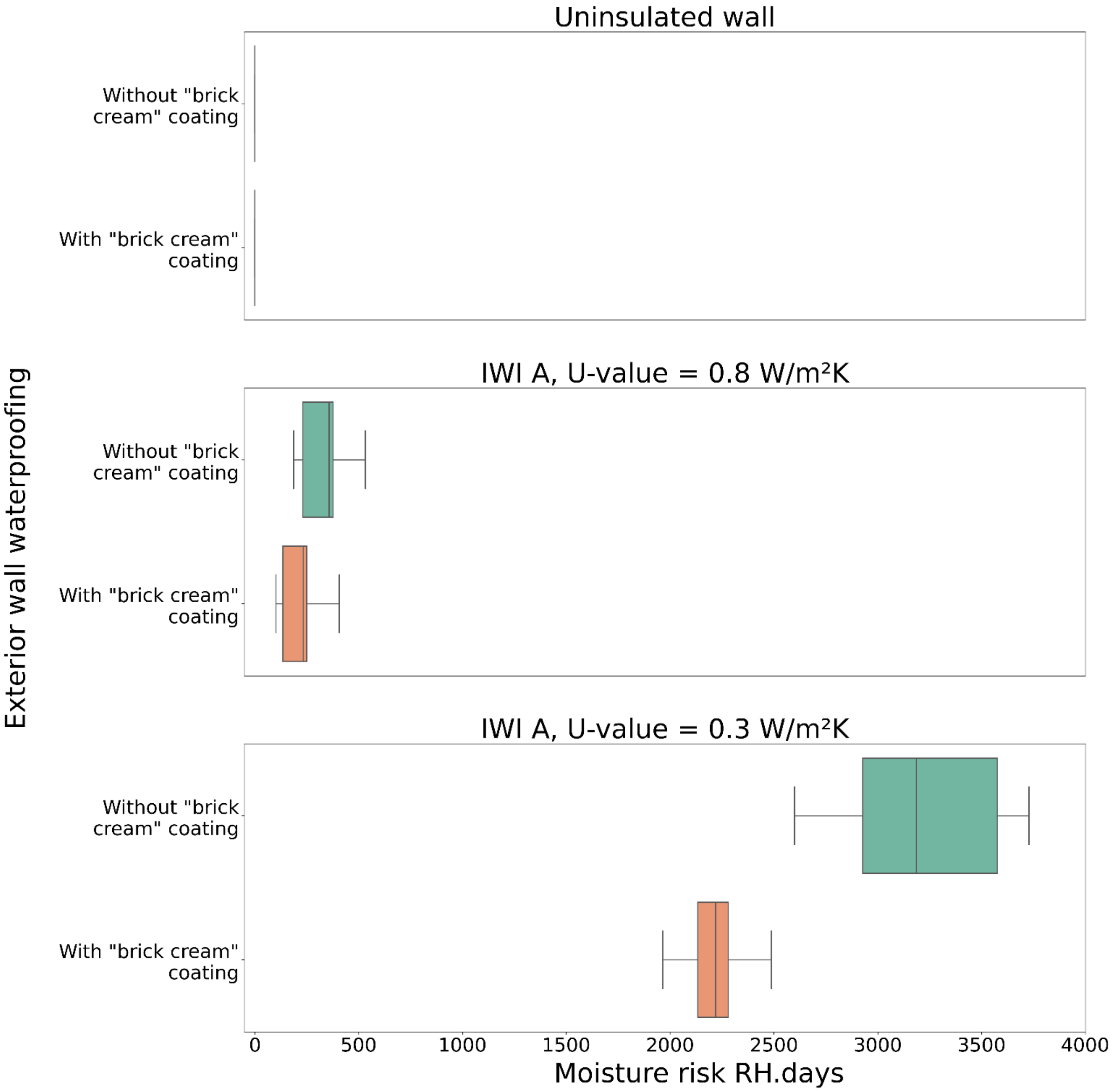
The relative moisture risk for the three cases, in each of the ten years of the RWD files for London, with and without the “brick cream” coating, are shown in Figure 25. The relative moisture risk is zero for the uninsulated wall regardless of the coating. For case 2 (U-value = 0.8 $W/(m^2{\cdot}K)$), the average relative moisture risk is reduced slightly from 32 RH.days to 17 RH.days by the “brick cream” coating. For case 3 (U-value = 0.3 $W/(m^2{\cdot}K)$), the average relative moisture risk is reduced from 1564 RH.days to 1094 RH.days by the “brick cream” coating.

Figure 25: Moisture risk RH.days in the uninsulated wall and two thicknesses of IWI A (wood-fibre), with and without the "brick cream" coating, simulated with the London RWD



The relative moisture risk for the three cases, in each of the ten years of the RWD files for Manchester, with and without the "brick cream" coating, is shown in Figure 26. The relative moisture risk is zero for the uninsulated wall regardless of the coating. For case 2 (U-value = 0.8 W/(m^2·K)), the average relative moisture risk is reduced slightly from 328 RH.days to 211 RH.days by the "brick cream" coating. For case 3 (U-value = 0.3 W/(m^2·K)), the average relative moisture risk is *reduced* from 3219 RH.days to 2209 RH.days by the "brick cream" coating.

Figure 26: Moisture risk RH.days in the uninsulated wall and two thicknesses of IWI A (wood-fibre), with and without the "brick cream" coating, simulated with the Manchester RWD file



Based on these results, the "brick cream" coating may result in a reduction in the relative moisture risk when the U-value is equal to 0.3 $W/(m^2 \cdot K)$ and the moisture risk is relatively high. However, at this level of insulation, the moisture risk remains relatively high, even with the "brick cream" coating.

6. Discussion and conclusions

A new method to quantify the relative moisture risk was developed for the DEEP project to explore the risk of installing (IWI). This was necessary as there is no accepted standard way to quantify risk. The method uses ten-years of weather observations from a Recent Weather Decade (RWD) file and a standardised method to calculate the temperature and RH profiles in the home. The resulting moisture risk RH.days can be compared to understand if an intervention is increasing or reducing risk. This method will be applicable to scenarios other than IWI.

The method was applied to a typical solid wall located in London and Manchester. In all cases, applying IWI increased the relative moisture risk. The moisture risk was higher in Manchester than in London. This would be expected as the weather in Manchester has a higher potential to wet a wall (higher exposure to wind driven rain) and lower potential for drying (lower air temperatures and solar irradiance) than London.

The wood-fibre vapour permeable IWI produced a relatively lower risk than the EPS with (AVCL) vapour impermeable IWI. When the EPS was simulated without the AVCL, the risk for EPS was reduced as the wall could dry out to the internal environment. However, the lowest risk was still for the wood-fibre vapour permeable IWI.

Increasing the thickness of the IWI increased the relative moisture risk in all cases. No safe limit exists for moisture risk and so a threshold insulation thickness cannot be quantified. However, the results showed that the relative moisture risk increased more rapidly below a U-value of about 0.8 $W/(m^2 \cdot K)$. This is similar to the threshold U-value of a renovated wall, according to the building regulations [1], of 0.7 $W/(m^2 \cdot K)$[17]. Thin IWI could reduce space heating energy demand (by around 20% for U-value = 0.8 $W/(m^2 \cdot K)$, compared with 30% for U-value = 0.3 $W/(m^2 \cdot K)$) while minimising moisture risk. However, long-term field work is needed to determine a suitable threshold of risk/benefit in different weather/exposure locations.

The walls were initially modelled at the orientation that maximised their exposure to wind-driven rain in each location. This approach was adequate for a comparative assessment, when U-value is lower than 0.8 $W/(m^2 \cdot K)$.. Nevertheless, it should be noted that moisture risk can be higher at other orientations, and much more notable at a U-value of 0.3 $W/(m^2 \cdot K)$ than at a U-value of 0.8 $W/(m^2 \cdot K)$. The impact of orientation on moisture risk was minimal when moisture risk was minimal, but orientation should be considered when the moisture risk is higher.

The stochastics of occupancy are ignored in this method of quantifying relative moisture risk. Homes with a higher moisture load will have a higher moisture risk. It would be sensible to ensure homes can be adequately ventilated to remove moisture from activities such as cooking, bathing, and laundry. This highlights the importance of holistic retrofit that overcomes

[17] In the building regulations it is also stated that the 0.7 value can be lowered due to interstitial and surface condensation; compliance with Part C is required in this case.

the barriers to improving ventilation (e.g., noise, security and air pollution) ensuring that maximum indoor RH is reduced. Ensuring that RH remains within some acceptable limits is of vital importance since as it was shown in Section 5.3.3, even small changes in interior RH can have a significant and non-linear impact on relative moisture risk.

The hygrothermal properties of bricks had an impact on moisture risk, but this is not as important as the weather or the thickness of insulation. The water absorption coefficient was not a good indicator of moisture risk, on its own. It is therefore sensible to continue to develop the database of properties for different British bricks, and brick type should be considered when moisture risk is higher. However, the brick properties were not important at lower moisture risk. The use of a “brick cream” coating to waterproof bricks was not justified by this research as it only reduced the moisture risk when moisture risk was already relatively high.

Overall, the inherent variability in the weather over the ten years had a strong impact on the moisture risk in some cases more than others. The use of RWD files is therefore recommended over a weather file consisting of data of one only year. The use of thin IWI is promising, and future investigations should focus on the interplay between energy savings and moisture risk for different thicknesses of insulation.

References

1. H M Government. The Building Regulations Approved Document Part L1A. Conservation of Fuel and Power. Vol. 1. London: Department for Communities and Local Government; 2013.

2. Lingard J. Residential retrofit in the UK: The optimum retrofit measures necessary for effective heat pump use. Building Services Engineering Research and Technology. 2021;42(3):279–92.

3. Dowson M, Poole A, Harrison D, Susman G. Domestic UK retrofit challenge : Barriers , incentives and current performance leading into the Green Deal. Energy Policy. 2012;50:294–305.

4. Little J, Ferraro C, Aregi B. Assessing risks in insulation retrofits using hygrothermal software tools. Heat and moisture transport in internally insulated stone walls. 2015.

5. Heseltine E, Rosen J, editors. WHO Guidelines for Indoor Air Quality: Dampness and Mould. 2009.

6. PRP Architects LLP. Research into resistance to moisture in buildings -Using numerical simulation to assess moisture risk in retrofit constructions. Part 1. Ministry of Housing, Communities and Local Government; 2019.

7. Fraunhofer IBP.https://wufi.de/en/software/wufi-pro. WUFI Pro [Internet]. [cited 2021 Mar 17].

8. BSI. BS EN 15026:2007 - Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation. Vol. 3. London: British Standards Institution; 2007.

9. Mourkos K, Allinson D, Lomas K, Beizaee A, Mantesis E. Improved weather files for building simulation. DEEP Project Report 6.01. Building Energy Research Gropup (BERG) Loughborough University; 2022.

10. Arregi B, Little J. Summary Summary of WUFI Report on the Future Risks of Moisture in Internal Wall Insulation - Laboratory report. Building Life Consultancy. 2013.

11. HM Government. The Building Regulations Approved Document C: Site preparation and resistance to contaminants and moisture. 2004 edition (incorporating 2010 and 2013 amendements). London: Department for Communities and Local Government; 2004.

12. Tersteeg R. Capturing the impact of wind driven rain on solid-brick wall dwellings [Internet]. Thesis, Loughborough University; 2020.

13. Hersbach H, Bell, B. B, P., Biavati G, Horányi A, Muñoz Sabater J, Nicolas J, et al. ERA5 hourly data on pressure levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). 2018;

14. Glew D. DEEP Project Report 2.02 17BG. Leeds Beckett University (LBU); 2022.

15. Rirsch E. Energy Saving from Water Repellents. In: Salford Retrofit Conference 2012 Retrofit 2012 Conference Paper - University of Salford. 2012.

This publication is available from: https://www.gov.uk/government/publications/demonstration-of-energy-efficiency-potential-deep

If you need a version of this document in a more accessible format, please email: alt.formats@energysecurity.gov.uk
Please tell us what format you need. It will help us if you say what assistive technology you use.