Void conditions and potential for mould growth in insulated and uninsulated suspended timber ground floors

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1. Abstract

Purpose: Millions of properties have suspended timber ground floors globally, with around 10 million in the UK alone. However, it is unknown what the floor void conditions are, nor the effect of insulating such floors. Upgrading floors changes the void conditions, which might increase or decrease moisture build-up and mould and fungal growth. This paper provides a review of the current global evidence and presents the results of in-situ monitoring of 15 UK floor voids.

Research method: An extensive literature review on the moisture behaviour in both uninsulated and insulated suspended timber crawl spaces is supplemented with primary data of a monitoring campaign during different periods between 2012 to 2015. Air temperature and relative humidity sensors were placed in different floor void locations. Where possible, crawl spaces were visually inspected.

Implications: Comparison of void conditions to mould growth thresholds highlights that a large number of the monitored floor voids might exceed the critical ranges for mould growth, leading to potential occupant health impacts if mould spores transfer into living spaces above. A direct comparison could not be made between insulated and uninsulated floors in the sample due to non-random sampling and because the insulated floors included historically damp floors. The study also highlighted that long-term monitoring over all seasons and high-resolution monitoring and inspection are required; conditions in one location are not representative of conditions in other locations.

Value: This study presents the largest UK sample of monitored floors, evaluated using a review of current evidence and comparison with literature thresholds.

Key words: suspended timber ground floors, crawl spaces, retrofit, void conditions, moisture, mould growth

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2. Introduction

Suspended ground floor constructions are common in the USA, New Zealand, Australia (Hill, 2005, Coulter, n.d., Williamson, 2000, Cox-Smith, 2008) and throughout Europe (Meijer et al., 2009). In the UK there are an estimated 10 million uninsulated suspended timber ground floors (Shorrock, 2005),(Dowson et al., 2012) with an estimated 6.5 million and 4.5 million in France and Germany, respectively (Westoby, n.d., DStatis, 2013).

Insulating the millions of uninsulated floors in cold climate regions might lead to large carbon savings (Shorrock, 2005, Power, 2008), supporting carbon reduction policies. Additionally, insulating floors might improve dwelling airtightness and occupant thermal comfort (Pelsmakers, 2016, Saint-Gobain, 2014), but this remains poorly characterised at present. For example, floor insulation was highlighted as a cost-effective carbon reduction measure by Shorrock (2005), and around 60% to 90% of the heat loss through suspended timber ground floors might be reduced by insulating them, depending on interventions (Pelsmakers and Elwell, 2017). In England, between January 2013 and June 2015, around 200,000 suspended ground floor insulation measures were recommended (DECC, 2015a), though only 9,000 floors (or 0.5% of identified floors) were actually insulated under the ECO-policy and under the (meanwhile withdrawn) Green Deal (DECC, 2015b). In the Netherlands and Austria it is estimated that the proportion of uninsulated suspended ground floors might be as high as 57% and 70%, respectively (Meijer et al., 2009). The number of insulated and uninsulated floors in many regions is currently not well recorded (Boardman, 2005, Meijer et al., 2009) and the actual impact of the insulation installations (i.e. the thermal upgrade benefits and risks) remains poorly characterised.

In the UK a 150 mm minimum ventilation zone below the timber floor joists has been required since the 1860's-1870's, to avoid rotting (Muthesius, 1984). Historic information is provided in Douglas (1997) and Douglas (1998c), who notes that pre-1937 floors are unlikely to have damp-proof membranes. NBS (2013) provides guidance for moisture control in ground floors in the UK: new suspended timber ground floors require damp-proof courses protecting the timbers and usually a 100 mm concrete over-site ground cover to resist ground moisture, with the top of the over-site above external ground level. The 150 mm minimum ventilated zone below the joists (or insulation) is still required at present, alongside the requirement for ventilation openings to be 0.0015 m^2 per meter exposed wall perimeter, or 500 mm^2/m^2 of floor area, whichever is the greatest (NBS, 2013). BRE (1998) noted that existing floors often have less than the current minimum recommended ventilation areas. Yet BRE (1998) and Douglas and Singh (1995) recommend that existing floors with no over-site concrete need 0.0030 m^2/m ventilation opening area and until the early 1970s this was also the requirement in Scotland (Douglas, 1998a). It is however unclear what data these standards are based on and if such standards are sufficient to prevent timber rot [i], or whether they are overly cautious, leading to unnecessary heat loss and draughts.

Reduced void ventilation can also occur when (partially) blocking airbricks with insulating material, whether intentionally to reduce heat loss, or unintentionally. However, obstructing or reducing floor void ventilation can lead to build-up of moisture in the floor void (Rickaby, 2014, EST, 2006, BRE, 2000). Additionally, ventilation paths are likely to be altered during retrofitting with insulation, reducing upward airflow from the void through gaps and cracks to the spaces above (EH, 2010, Stephen, 1998). Insulating suspended ground floors leads to reduced winter heat loss to the external environment through the floor void, which also leads to higher relative humidity due to colder floor voids. These changes to the crawl space conditions might increase the risk of mould growth or timber decay as noted by for example Samuelson (1994) and Lstiburek (2008) for new insulated suspended ground floor constructions in Sweden and the USA, respectively. Mould spores can also transfer from the crawl space to the living spaces above, affecting occupant health (Airaksinen et al., 2004).

Knowledge of the pre- and post-insulated hygrothermal floor void conditions is of great importance to avoid structural damage and health issues. Hence in this study, empirical floor void data was collected to allow a preliminary investigation into the hygrothermal conditions of both insulated and uninsulated floor voids and to compare with mould growth thresholds found in the literature. The aim of the study was to combine and review current evidence related to floor void conditions globally and to reinforce and extend this global knowledge by the empirical local data collection in 15 different UK floor voids, the largest known sample of UK floor void conditions available. Additionally, an overview of practical monitoring issues and protocols is provided. Firstly, a global overview of available evidence related to uninsulated floor void conditions is presented, followed by a discussion of evidence available for insulated floors. Subsequently, the empirical data collection campaign is described, including instrumentation and research and analysis methods, followed by presentation and discussion of results. Special attention is given to a mould growth risk evaluation based on literature thresholds. Finally, a concluding summary is provided, focusing on practical implications arising from the findings.

3. Uninsulated suspended ground floor void conditions: a review of evidence

In the UK, an increased risk of damp and mould problems in dwellings built pre-1919 has been reported (DCLG, 2010), with around 5.8% of floors requiring repair of some kind (DCLG, 2010). In the USA, moisture problems have been reported since the 1940s (Rose, 1994), leading to a more significant body of research than in the UK.

3.1. Potential sources of moisture build-up

Moisture build-up in pre-1919 suspended floors can come from a variety of sources, e.g.: moisture from the ground, lack of external site drainage, leaks from services, impermeable floor finishes, external ventilation, floor insulation and surface condensation; these are each briefly discussed below and illustrated in *Figure 1.*

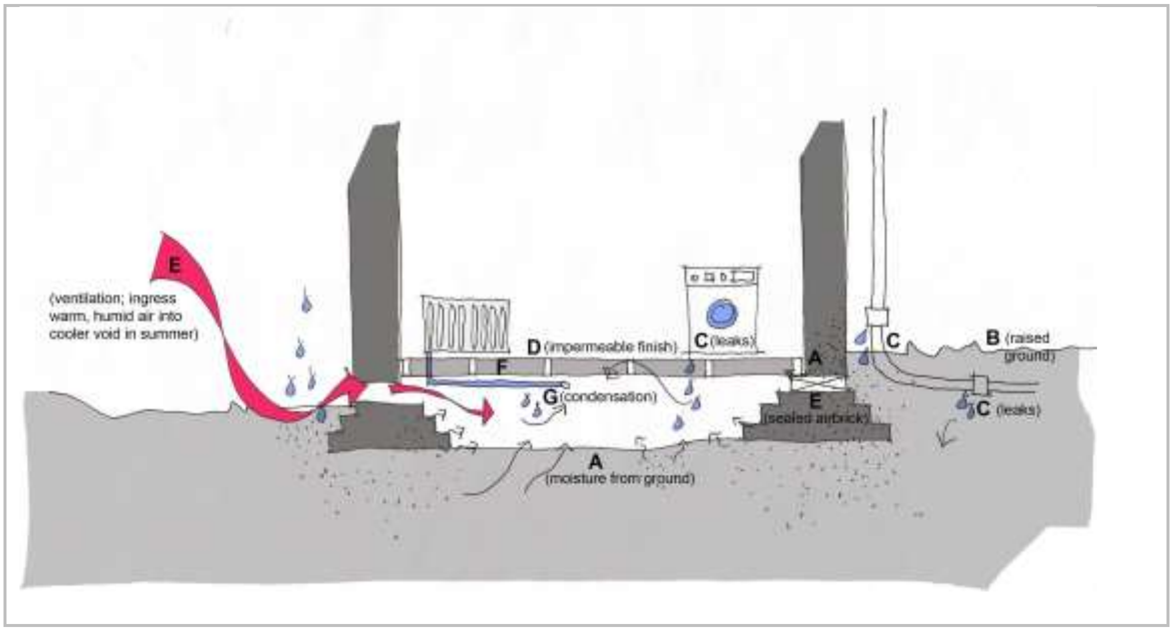

Figure 1. Possible sources of moisture in pre-1919 suspended timber ground floors; letters refer to letters in text below.

A. Moisture from the ground: wet soil (e.g. due to high ground water level) or standing water in the floor void could cause high evaporation rates and high relative humidity (RH) in the crawl space; this moisture can transfer to indoor spaces above (Harris, 1995). In most existing suspended ground floors, no ground cover exists (Douglas, 1998c) and evaporation from damp soil is considered a major source of moisture (Harris, 1995, Moses, 1954). In addition, joists supported by brick walls can become damp when timber joists are in contact with soil (Tsongas, 1994). Damp joists can also occur due to driving rain or 'splash back' or where joists are supported by walls with rising damp, especially a risk without damp proof membranes (Harris, 1995, Oliver, 1997, Douglas, 1998b, Ridout, Tsongas, 1994) - see Figure 2 and 3. Ground soil can be a moisture source during cold season but can absorb some moisture during summer time (Matilainen, 2003).

 

Figure 2. (left) and Figure 3. (right) illustrate a crumbling sleeper wall/dwarf wall in a Manchester (UK) crawl space, caused by high ground moisture. Joists were laid on a damp-proof membrane (indicated by arrow) to prevent immediate contact; while this protects from direct contact with damp surfaces, this does not protect from high RH in the floor void itself. Figure 3. Illustrates a DIY installation of the ground cover (indicated by arrow) to reduce evaporation of moisture from the ground; in some cases condensation water can pool on the membrane, as was the case here.

B. Inadequate external site drainage and/or external ground level can be above floor level so that water can enter floor voids (Rose, 1994, Brook, 1994, Oliver, 1997, Singh, 1998).

C. Leaks from services can occur above/below the floor or leaks from rainwater runoff pipes nearby (Brook, 1994, Tsongas, 1994, Morton, 2013). Spillage from living spaces above is probably rare (Harris, 1995) and both spillages and leaks are likely to be localised (Douglas, 1998b). However, this can still lead to localised mould growth as illustrated in Figure 4.

Figure 4. Mould growth in the void area (indicated by arrow), caused by a leaking rainwater pipe, wetting the brick walls down to foundations in a London (UK) crawl space. This leak occurred in the final 12 months of a 3 year monitoring period, highlighting the dynamic nature of void conditions, and their interaction with whole house mechanisms.

D. Impermeable floor finishes might prevent moisture transfer to the spaces above where previously this was possible and may induce a critical wood moisture content (BRE, 1991). This includes insulation materials and membranes in the construction.

E. Ventilation plays a complex role in managing moisture risk. For example, moisture will be brought in from the outside through airbricks and other non-airtight paths, but can also increase the swift dispersal of moisture build-up (Kurnitski, 2001) especially in winter (Hill, 2005), though this may not always be effective (Harris, 1995). Douglas (1995) acknowledges that even when voids are well ventilated, humidity can build up in void recesses. Furthermore, increased ventilation leads to an increased evaporation rate from damp soil and other moist surfaces which can increase moisture build-up in the floor void, despite increased ventilation rates (Harris, 1995, Kurnitski, 2000a). Furthermore, Hill (2005) argues that ventilation on its own is insufficient to deal with significant amounts of moisture build-up in floor voids and summer-ventilation can increase moisture build-up risk. In summer, warm, humid air enters the generally cooler floor void thereby increasing RH; however, in winter, cold and more dry external air is warmed in the void, decreasing RH (Vanhoutteghem, 2017, Richter and Staněk, 2015). The high thermal mass of the ground reduces the impact of the warm summer air on increasing the temperature of the floor void: it is cooled and RH increases (Kurnitski, 2001, Airaksinen, 2003, Rose, 1994, Hill, 2005, Samuelson, 1994). This can lead to summer surface condensation in the void - see point F. below.

A lack of void ventilation, e.g. due to sealed airbricks, is considered by many to be the cause of moisture build-up in floor voids (Oliver, 1997, Burke, Douglas, 1998c, Douglas, 1998a, BRE, 1991, Singh, 1998). This (partial) sealing of airbricks can occur when installing floor insulation (Figure 5); chamfering floor insulation could reduce this risk (Figure 6). However, a sealed void is reported by others to prevent moisture build-up in summer (Rose, 1994, Samuelson, 1994, Lstiburek, 2004) for the reasons described above. Nevertheless, Kurnitski (2001) points out the difficulty associated with sealing airbricks to control summer moisture ingress because air can enter the crawl space via other ventilation paths. All of these observations are based on non-UK climates and constructions; for the UK climate, Oliver (1997) notes the increased risk of condensation when sealing floor void air-vents in winter, especially when these are blocked in summer. Clearly, outdoor air cannot dry the floor void if it infiltrates at a higher moisture content than the floor void itself and instead will bring moisture in. Hence Kurnitski (2001) argues that if there is no moisture source in the void (i.e. if the void is 'moisture insulated') there is no need to ventilate, but acknowledges that *"any leakage in the moisture insulation can bring about high relative humidity"* (Kurnitski, 2001). Sealing of airbricks is considered undesirable when radon is present, however this discussion is excluded here.

Figure 5. (left) and 6 (right) Illustrates a blocked airbrick, unintentionally caused by placing rigid insulation boards between the joists. Figure 6. illustrates chamfering of the insulation to aid instead of obstruct airbrick airflow.

F. Installation of floor insulation might lead to colder void air and surface temperatures, impacting on void moisture conditions (Samuelson, 1994, Airaksinen, 2003). In Finland, Airaksinen (2003) reported that floors with a typical U-value of 0.2 $Wm^{-2}K^{-1}$ had an average modeled void RH almost 10% higher than floors with 0.4 $Wm^{-2}K^{-1}$ U-value; the less insulated floors were predicted to have a 2ºC warmer void air temperatures on average (Airaksinen, 2003). Section 4 discusses insulating floors in more detail.

G. Surface condensation can occur when the void air reaches its moisture vapour saturation point at a given temperature and condenses against surfaces in the void which are below the dew point temperature. This might occur especially in summer when warm, humid air meets for example cold, uninsulated metal pipes or other cold surfaces (Lstiburek, 2008, Hill, 2005).

3.2. Moisture risks in floor voids

3.2.1. Risk of mould growth and wood decay

The main danger of moisture build-up in floor voids is that it can lead to fungal growth and timber decay (Moses, 1954, Singh, 1998, Oliver, 1997). Most occupants do not notice the presence of fungal growth or timber decay until some incident indicates its presence (Frankland, 1951), such as fine red dust (caused by dry rot spores) on floor surfaces (Morton, 2013, Ridout) or springy floors (Singh, 1998) or failure of floorboards or floor joists (BRE, 1998).

The organisms of concern in floor voids are wood rotting fungi (such as dry and wet rot) and non-wood rotting fungi, which either grow on timber or on other materials. Wood can have a high Wood Moisture Content (WMC) if directly in contact with wet surfaces, but also due to a high ambient RH in floor voids: timber as a hygroscopic material will absorb moisture from the atmosphere until in equilibrium with the surrounding air (Ridout, 2001). The lower the WMC, the less susceptible the material is to decay (Oliver, 1997) and this is ideally below 15% WMC (Ridout, 2001) (or <75% RH (EH, 2010)). Timber decay does not generally occur below 22-24% WMC, often lowered to 20% as a safety measure (Ridout, 2001) (or equivalent to around 90% RH (EH, 2010)). EH (2012), on the other hand, reports that timber decay might not occur below 28-30% WMC, which is associated with a relative humidity level of at least 95%.

Airborne spores can be a health hazard - see section 3.2.2. - but in all cases remedy and prevention of moisture build-up and water penetration eventually kills the fungus (Ridout, 2001, Oliver, 1997) and reduces occupant exposure. Wet rot requires higher moisture thresholds: 20-25ºC with WMC above 30% (Ridout, 2001, Douglas and Singh, 1995) (i.e. ~100% RH); with optimal WMC of 50-60% (Oliver, 1997). Dry rot is one of the most common fungi in buildings in the UK (Douglas and Singh, 1995) and can grow rapidly at 21-23ºC with WMC of 30-40% (Douglas and Singh, 1995, Oliver, 1997), requiring >90% RH at minimum 20ºC (Ridout, 2001). It can grow at lower thresholds, though decay will be slower; ideal conditions for growth are RH of 99% (or 26-30% WMC) (Ridout, 2001). Dry rot's food source is timber or other cellulose based materials (Douglas and Singh, 1995) and it needs a source of calcium, which is present in damp cement/lime mortar and in plaster (Ridout, Douglas and Singh, 1995), and other organic material, such as rock or glass wool insulation (Douglas and Singh, 1995), commonly used in buildings (EH, 2010), including suspended floors. Dry rot also favours stable, unchanging environments (Ridout, 2001).

For mould growth, thresholds are lower. Typically, mould growth can be initiated on timber in conditions of >70% RH at room temperature (Oliver, 1997); however mould fungi do not tend to decay timbers but have superficial growth and may stain surfaces (Ridout, 2001). Mould can grow on EPS and mineral wool insulation during long-term exposure to RH >97% (Viitanen, 2007). At very high RH (> 97% RH or wet materials) bacteria also cause smell and health problems similar to mould fungi (Viitanen et al., 2010). Even in dry air conditions, mould can grow on wet and nutrient rich surfaces. At temperatures lower than 10ºC, which are less ideal for fungal growth, growth occurs slowly, but could "*accumulate considerably during years and decades in the life of a building*" (Pasanen, 1991a), yet conditions are poorly characterised for floor voids. In floor voids, RH conditions of 80-85% over several weeks or months can lead to mould growth as temperatures are usually above 5ºC (Kurnitski, 2000b).

As timber rot requires higher RH conditions and usually longer exposure times compared to mould growth (Viitanen et al., 2010), mould growth risk tends to be used as a threshold to evaluate a construction's condition (and thereby avoiding more severe risks) (Airaksinen, 2003, Johansson, 2012, Sedlbauer, n.d., Viitanen et al., 2010, Hukka, 1999). Different evaluation criteria can be found in the literature, ranging from single value thresholds (Gradeci, 2017, Johansson, 2014, Sedlbauer, 2001) over isopleth systems (Smith, 1982, Sedlbauer, 2001, Clarke, 1999) to more sophisticated models (Sedlbauer, 2001, Viitanen et al., 2010). Johansson (2014) states critical RH thresholds for wood (based) materials ranging from 75% to 89% at 22°C and between 75% and 95% at 10°C. Sedlbauer (2001) concludes that the lowest humidity that can induce mould growth in buildings is approximately 70%. The latter is also the lowest critical relative humidity in the overview summarised by Gradeci (2017) whose literature review indicates critical RH between 70% and 85%.

Isopleths are curves of RH threshold as a function of the temperature (Figure 7). Simple isopleth curves, such as used in the ESP-r model (Clarke, 1999, Rowan, 1999), or presented by Smith (1982) or Hens (1999), describe the lowest conditions with significant mould growth risk and are specific to mould spore type. However, Sedlbauer (2001) developed a lowest isopleth for mould (LIM), below which no mould will grow but also isopleths indicating the critical RH and temperature threshold to initiate mould spore germination for a specified time (e.g. 1, 2, 4,… days). Additionally, Sedlbauer (2001) developed isopleths indicating the mould growth (in millimeters) per day as a function of the relative humidity and temperature. Isopleths for specific types of moulds, different health hazardous classes (health class A, B and C) as well as material substrates (substrate category 0 till III) can be found in literature. Figure 7 gives a comparison of a selection of lowest isopleths for mould growth: (1) the ESP-r threshold for xerophilic [ii] mould spores, (2) Sedlbauers' LIM-curves for substrate category I (biologically recyclable building materials), substrate category II (building materials with porous structure such as certain wood species) and health class B/C (fungi that are pathogenic when exposed to over a long period and fungi that are not pathogenic) and (3) the critical threshold suggested by (Hens, 1999). Additionally, the critical relative humidity level as included in the VTT model is shown (Hukka, 1999).

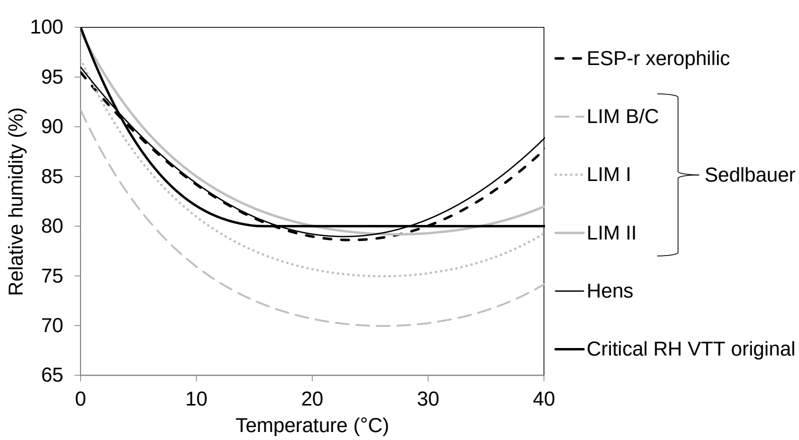

Figure 7. Comparison of a selection of isopleths (ESP-r and Sedlbauer) and the critical relative humidity included in the

VTT model.

Predicting mould growth based on the single value thresholds and the isopleths is challenging because in-situ conditions affecting mould growth usually fluctuate with the (e.g. diurnal and seasonal) weather conditions; this is especially the case for the dynamic floor void conditions. For example, an interim drying out of the mould spores cannot be taken into account in such predictions. A possible way to deal with fluctuating conditions could be applying Moon's germination graph method (Moon, 2005), though the way a transition from favourable to unfavourable conditions and vice versa is included in this method deviates from practice (Vereecken and Roels, 2012).

To enable a prediction or evaluation of the mould growth risk under dynamic conditions, within years, more sophisticated mould prediction models are usually used. In this respect, the VTT model (Hukka, 1999) and the WUFI-Bio biohygrothermal model (Sedlbauer, 2001, Krus, 2007, WTA, 2006) are two models frequently applied in the building physics field (e.g.(Airaksinen, 2015, Langmans, 2015, Holzhueter, 2017)). As is the case for the single threshold values and the isopleths, these more sophisticated mould prediction models are mainly developed based on controlled – steady state – laboratory studies (Oreszczyn, 1999). Despite focusing on wood not commonly used outside Scandinavia and despite exclusion of dust contaminated samples (Vereecken and Roels, 2012), which are likely to be found in floor voids, the benefit of the VTT-model is that it has been validated with in-situ monitored floor void mould growth and temperature and RH profiles typically found in (Finnish) floor voids (Airaksinen, 2013). The WUFI-Bio biohygrothermal model, however, is limited to indoor building surfaces (Sedlbauer, 2017), as also discussed by Marincioni (2017); floor void environments are likely characterised by lower air and surface temperatures and seasonally different RH conditions than the internal surfaces assumed in WUFI-Bio. Ultimately, the big differences between lab and in-situ conditions can make mould growth predictions unreliable and variant between models (Vereecken and Roels, 2012, Vereecken et al., 2015, H. Altamirano-Medina, 2009). Therefore, in the current study a preliminary assessment of the 15 floor void conditions is performed based on the critical (isopleth) thresholds only (see section 5.2).

3.2.2. *Floor void moisture build-up and potential health impacts*

Occupant health might be affected prior to any visual manifestation of issues, as contaminants (such as fungal spores, microbes and bacteria which can thrive in moist environments) can be transferred from the floor void into living spaces as noted most recently by among others, Kroger (2007), Hill (2005), Airaksinen et al. (2004), Lilly (1988), McGrath (1996), Coulter (n.d.) and Frankland (1951). Dampness and mould exacerbate asthmatic conditions (Frankland, 1951, WHO, 2009) and fungal spores are associated with respiratory problems (Park et al., 2004, Verdier et al., 2014). Moist environments can also give rise to the production of MVOCs (Microbial Volatile Organic Compounds) by fungal and microbic organisms (Paavilainen, n.d.) which can affect human health (Korpi et al., 2009, Fiedler et al., 2001). As such the transfer of air from contaminated floor voids into internal spaces is a significant concern for occupant health (Airaksinen, 2007).

In Finland, fungal spores in insulated floor voids were observed to be 10 times higher than internal spaces; usually highest on timber materials. These microbial and fungal contaminants can then be transported from the floor void to the indoor spaces, which are continuously mechanically ventilated (Airaksinen, 2003). Stack-effect driven airflow from void to internal spaces was observed in naturally ventilated dwellings in the UK (Hartless, 1999, Hill, 2005). Both stack-driven and wind-driven infiltration from the void is likely to find its way into internal spaces (Hartless, 1994), enabling the spread of fungal spores in living spaces (Figure 8). However, with an airtight floor, no fungal spore transfer was observed through concrete and EPS or PUR layers (Viitanen et al., 2010), while through solid concrete floors, the air infiltration is less or even negligible depending on construction (Sherman, n.d.). However, for timber floors: "*penetration of fungal spores is difficult to control by sealing and by controlling the airtightness of the building envelope*" (Airaksinen, n.d.). Balanced building ventilation with equal air intake and extract might be an effective measure instead (Airaksinen, n.d.).

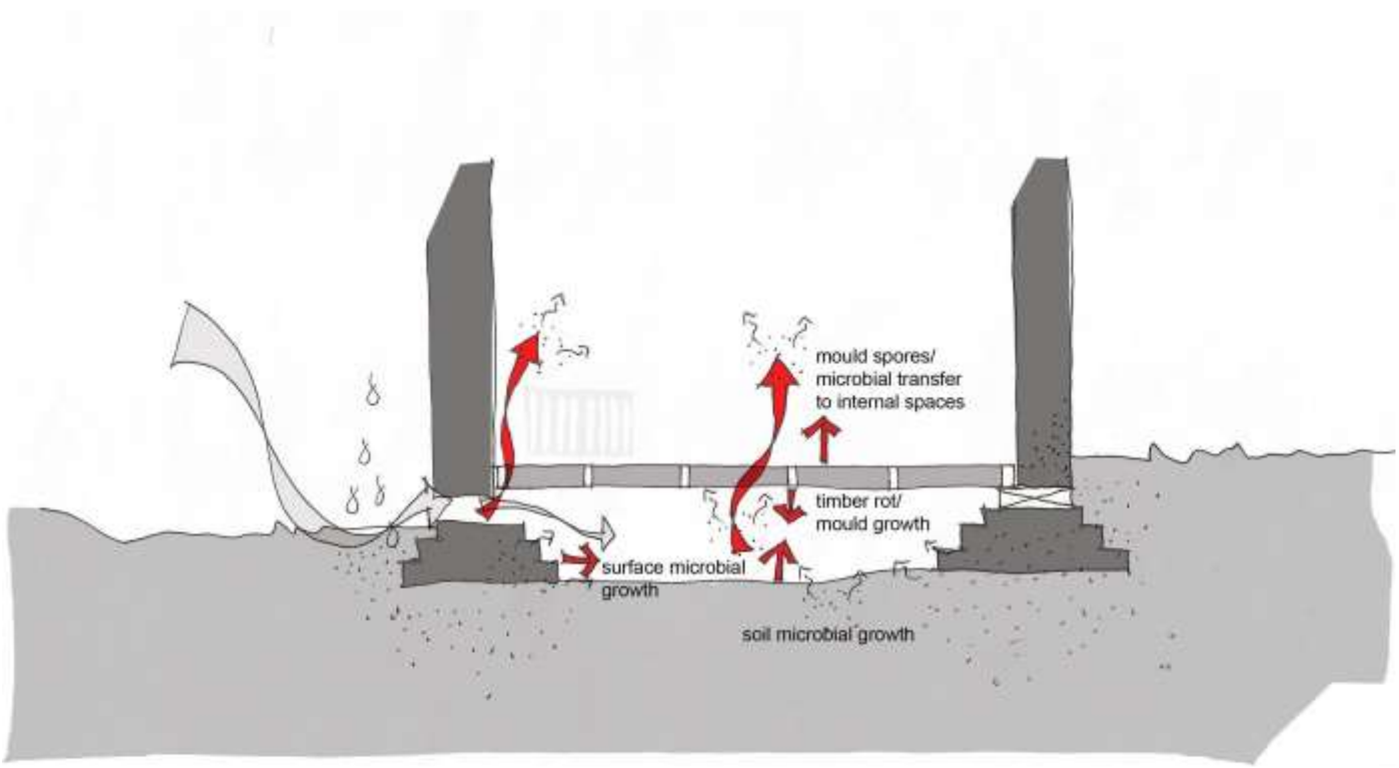

Figure 8. Sources of mould and microbial growth could transfer to internal spaces - diagram adapted from (Airaksinen, 2003).

4. Insulated suspended ground floor void conditions: a review of evidence

Insulated ground floors are poorly characterised at present, however some sources refer to the potential increased risk of moisture build-up in insulated suspended ground floors. For example, Shrubsole (2014) and others (Energy_Solutions, n.d.) note that adding floor insulation can increase the risk of unintended consequences, such as condensation on service ducts and pipes, potentially leading to mould growth and timber decay (Coulter, n.d.). Insulated floor void spaces in Finland experienced optimal conditions for fungal growth (Hukka, 1999, Pasanen, 2001), especially with high (>80%) RH in summer, regardless of the ground cover and with temperatures in the floor voids between 10ºC and 17ºC (Pasanen, 2001). In the USA there are reports that insulated floors have moisture issues, in some cases leading to mould growth and wood rot (Lstiburek, 2008, Hill, 2005, Flynn, 1994, Coulter, n.d., ASHRAE, 1994). However, Harris (1995) suggests that condensation risk in insulated floors might be minimal. Similarly, Tsongas (1994) reported almost non-existent long-term moisture-related issues for a varied sample of 121 floor voids (insulated, uninsulated, ventilated and unventilated) in 5 different locations in the Northwest of the USA. Timber decay (including historic) was only observed in a few floors with plumbing leaks or on wood in contact with soil.

High summer humidities were reported in insulated floor voids in Sweden and Finland (Burke, Matilainen, 2003, Kurnitski, 2000b), in the USA (Coulter, n.d., Lstiburek, 2008) and in a test cell in Germany (Werther, 2010). Tsongas (1994) associates the moisture-issue absence in the 121 floor void sample due to the local climate's dry summers unlike in other regions of the USA. Furthermore, summer surface condensation can be exacerbated by uninsulated air-conditioning ducts running through the floor voids (Lstiburek, 2008, Tsongas, 1994). Table 1 presents insulated floor void condition data as measured in Nordic counties and highlights that in several cases critical mould growth thresholds are met or exceeded.

VOID temperature (ºC)	VOID RH (%)	Source + notes
10 to 17ºC	**60-95%**	Pasanen (2001), measured May to September; mid-summer highest RH; above 80% RH for 8 weeks. Different ground covers; assumed insulated floors (not explicitly stated).
n/a	**90-95%** summer near foundation walls **60-70%** in winter near foundation walls	Samuelson (1994), insulated floor; ventilated void; study of the effect of different ground covers as measured

	80-90% both summer & winter, with ground insulation	
Air Temp: 7-19.5ªC	**68%-88%** no ground cover **50%-75%** plastic ground cover	Kurnitski (2000b), approximate RH and void air temperature, as measured
n/a	**67%-84%** natural ventilation	Kurnitski (2001), modelled

Table 1. Observed void conditions in dwellings subjected to Nordic climate and usually over several seasons; typically based on insulated floor voids.

Whether the floor void conditions reach or exceed critical mould growth thresholds will depend on many variables and characteristics, including winter but especially summer climate, floor insulation thickness and characteristics, ventilation and construction, alongside the presence of moisture sources, presence of (uninsulated) services in the void and moisture management solutions. Some possible floor void moisture management includes: ground covers, ground insulation, and mechanical void ventilation when void conditions reach critical levels (Airaksinen, 2003, Samuelson, 1994). However, without further evidence and research that takes these different variables into account, no clear conclusions can be drawn on the nature of the increased moisture build-up risk in insulated suspended ground floors. Note that insulating floors could also lead to other unintended consequences, such as an increased fire risk if old electrical wires are embedded, a risk of burst water pipes in colder voids (EH, 2010) and radon build-up (Lugg, 1997) - see Figure 9.

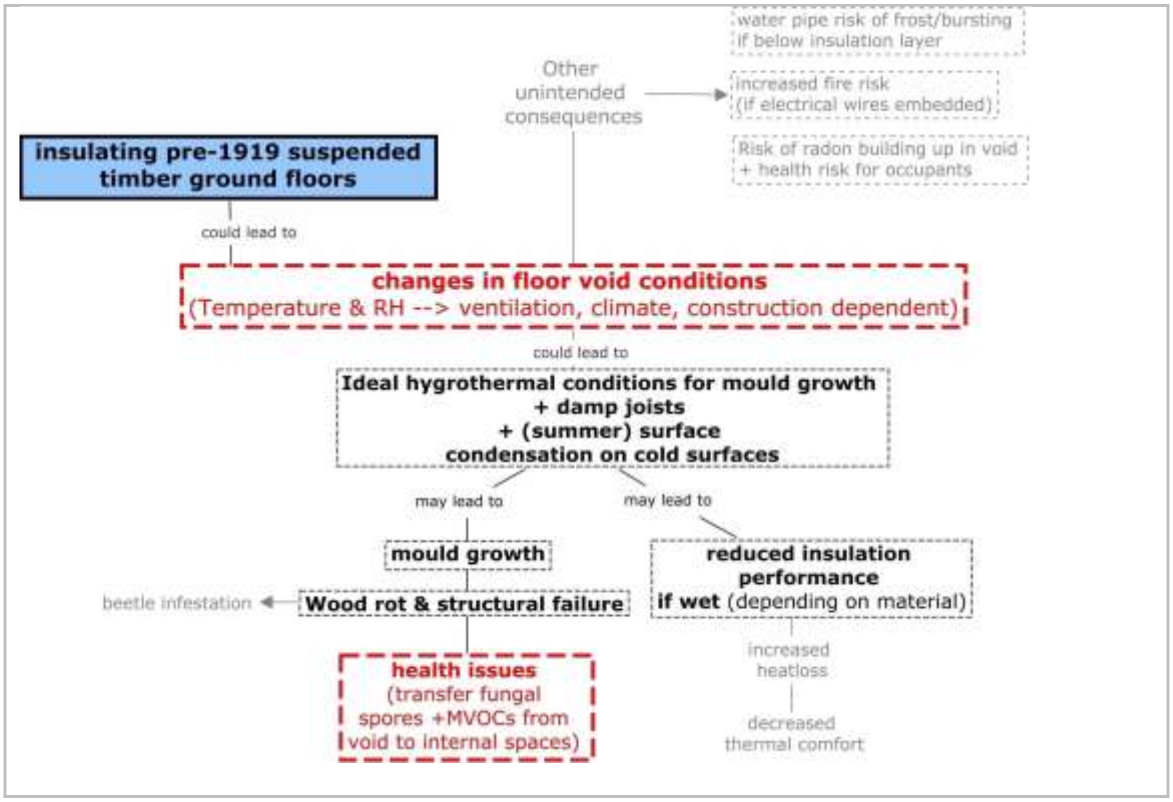

Figure 9. Possible unintended consequences associated with insulating floors

5. Floor void monitoring campaign

A sample of 15 different UK floor voids were monitored for varying lengths of time between 2012 and 2015; a summary is provided in Table 2. Data was collected from nine insulated floors and six uninsulated floors; two floors (Floor 6 and 8) were also measured pre-insulation, while Floor 9 consisted of an insulated and uninsulated section; both of which were monitored. The total of nine insulated and nine uninsulated floor void monitoring periods are presented here. The monitoring of Floors 6 and 8 pre- and post- insulation was undertaken for short periods of time and across different seasons. In addition, sensor locations in Floor 8 were not the same due to the intervention. Hence no robust comparisons are possible between pre-post void conditions for either floor.

	Characteristics	Number of sensors	approx. airbrick ventilation (m2/m)
Uninsulated floor samples			
Floor 1	North London, void depth ~ 300 mm; 100 mm joists; bare soil; bare floorboards.	7 (different duration)	0.0011
Floor 2	North London, ~300 mm void depth; 100 mm joists; bare floorboards; bare soil	1	0.0012
Floor 3	solid oak tongue & groove floorboards over original boards	1	0.0007
Floor 4	Reading, ~800 mm void depth; 100 mm joists; bare floorboards; bare soil.	4	0.001
Floor 5	Cambridge, ~250 mm void depth; 100 mm joists; bare floorboards; bare soil.	4	0.0011
Floor 6	West London, uninsulated, sensors near ground; one in front and in back of void	6	0.0024
Floor 7	West London, ~600 mm void depth; 100 mm joists; bare floorboards.Sensors 200mm below joists near and further away from airbricks	3	0.0011
Floor 8	Manchester, uninsulated, measured near joist and 200mm below joist; near airbricks	2	0.0009
Floor 9	South-East England, Measured in uninsulated part of floor; Sensor near airbricks: Gemini Tinytag Ultra 2 (±0.4ºC, ± 3%; 0% to 95% RH).	1	n/a
Insulated floor samples			
Floor 6	West London, 100mm woodfibre insulated; sensors near ground; one in front and in back of void	11	0.0024
Floor 8	Manchester, Insulated with 100 mm Knauf earth wool insulation, tongue-grooved chipboard, carpeted; measured near joist and 200mm below joist; away from airbricks	2	0.0009
Floor 9	South-East England Measured in insulated part of floor- 100 mm mineral wool; , Sensors further away from airbricks: Gemini Tinytag Ultra 2 (±0.4ºC, ± 3%; 0% to 95% RH).	1	n/a
Floor 10	Manchester, nsulated basement with wood fibre insulation; sensor at 300 mm and 500mm below joist	2	n/a
Floor 11	South London, sealed airbricks, loose filled graphite coated EPS bead insulated floor void. Airbricks sealed and full-fill void (approx. 450 mm); sensors in different heights in void; all near external wall; 1 sensor 1m away from wall	7	0
Floor 12	West London, 100 mm sheep insulation; sensor near airbricks, 400mm deep into 800 mm deep void	1	n/a
Floor 13	Herefordshire, sealed airbricks; 150 mm mineral wool insulation; Sensors: under floorboard; in insulation;150mm in void below insulation; sensor specification: DS-1923 i-button (0-100% RH; ±0.5ºC, ±0.6%RH)	3	0
Floor 14	South London, 80 mm mineral wool insulated; plastic ground cover; sensor: approx.500 mm below joist on timber batten on ground	1	0.0015
Floor 15	Brighton, sealed airbricks, EPS full fill bead insulated; senosrs: near external wall and further away, in middle of void; Gemini Tinytag Ultra 2 (±0.4ºC, ± 3%; 0% to 95% RH).	2	0

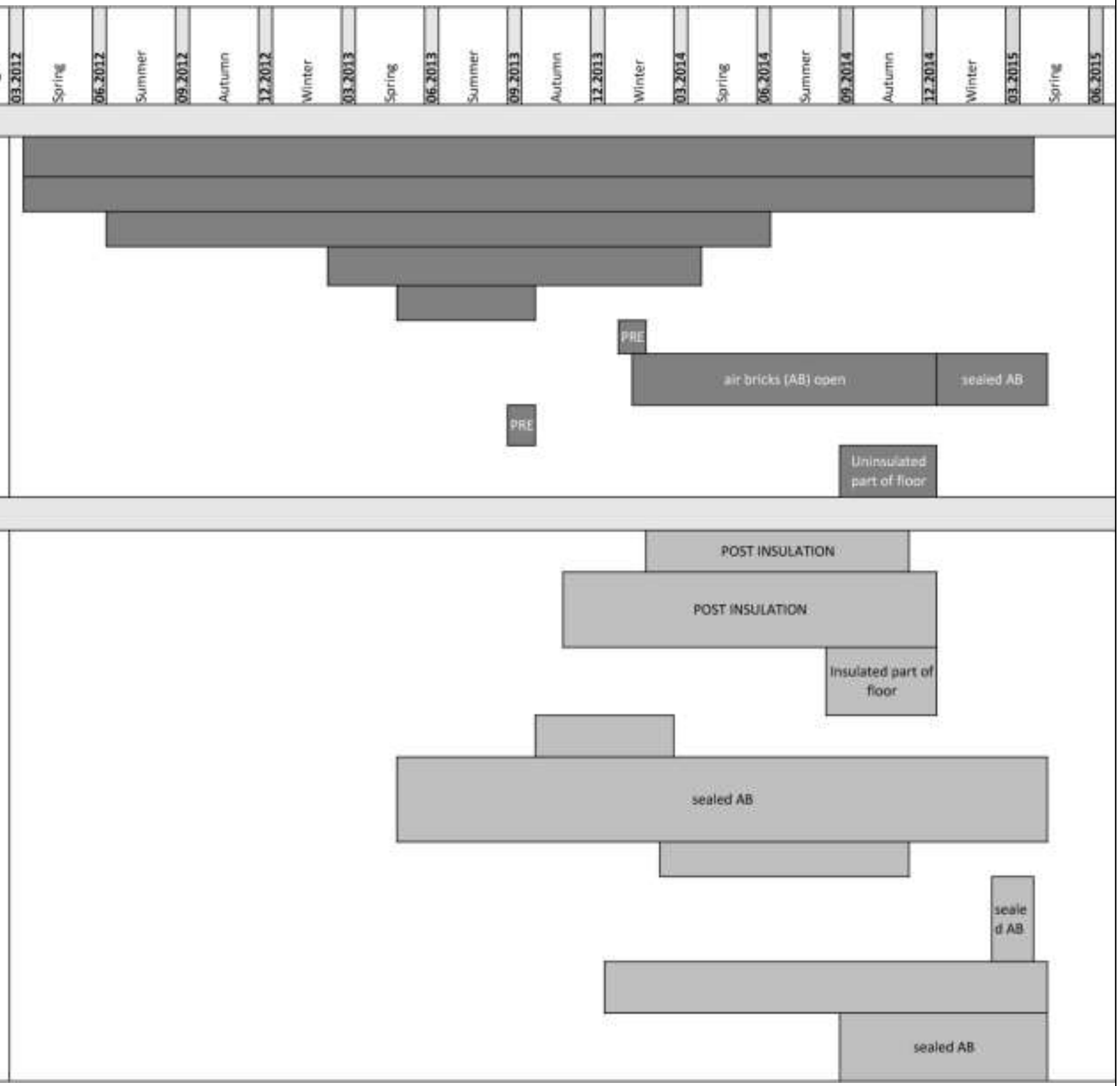

Table 2. Summary of uninsulated and insulated floor void monitoring sample and number and specification of sensors per floor and monitoring timeline. Use of HOBO U12 sensors (±0.35ºC and ± 3% RH, up to 95% RH) unless stated otherwise. Note that the measured floor void ventilation generally fell below current UK building codes of 0.0015 m²/m.

5.1. Research methods and sampling

All ground floor crawl spaces were located in the UK and were of suspended timber construction; one floor had a basement underneath (Floor 10). Three of the insulated floors had sealed airbricks (Floors 11, 13, 15), while all the other floors were naturally ventilated through the airbricks. The floor void of Floor 11 and 15 were fully-filled with EPS insulation beads. Sample size was limited by availability of accessible floors.

There are many different dwelling and floor archetypes, and each floor is subject to different variables, so that a comparison between floors remains difficult. Due to this diversity, and the statistically small sample of 15 floors, the floors would not be representative of the wider population, even if randomly sampled. However, the intention of the study was not to compare the floors with each other, but rather to explore the seasonal and spatial conditions in different floor voids, and compare this to literature thresholds, as well as to contribute to methodological insights and implications to support future studies. Given that the purpose of the study was to explore and to gain an increased understanding of different floor void conditions, and methodological implications, case studies were identified by convenience or self-selection sampling. Hence, some 'extreme' cases (Saunders, 2009) were monitored; for example some insulated floors were included after stakeholders approached the authors wishing to participate due to previously identified issues with moisture build-up in the floor void (e.g. Floors 13, 14 and 15), or concern about the impact of the insulation intervention on the void condition (Floor 11). Additionally, the sample includes floors with bead-filled voids and sealed airbricks (e.g. Floor 11) as well as monitoring of void conditions with a history of dampness and/or mould growth (Floors 11, 13, 14, 15), and this further contributed to an intentional heterogeneous selection of cases with many different variables. Given the purposeful inclusion of cases with historical mould risk factors, the study was able to provide insights into the characteristics of non- and "at risk" voids, exploring the methodological implications and the variation of floor void conditions. To abide by research ethics, any potential identified risk to human health or structure was shared with property owners as soon as this became apparent from data collection or visual inspection.

Instrumentation

For primary data collection, HOBO U12 sensors (±0.35ºC and ± 3% RH) were used, unless otherwise stated in Table 2. Initially, variables were monitored every five to ten minutes, however due to data logger memory and access limitations, some data was periodically lost. Hence the logging intervals were increased to 60 minutes, which is the data-interval required for the post-processing procedures used in most models. Some missing data also occurred due to failed batteries and where floor void conditions recorded ≥95% RH (HOBO U12 sensor limitation) for extended periods. In cases where access was not possible, sensors were mounted on retractable and pivotable timber posts to help insert and retrieve the sensors. Areas away from uninsulated radiator pipes were sought (visible with IR camera when sensor installation in the heating season).

Each floor was longitudinally monitored for relative humidity (RH, %) and air temperatures (ºC), with a total of 59 sensors placed in-situ in 15 floor voids. Where possible, more than one location and at different heights in the void were monitored to gain a better understanding of the spread of temperature and RH in the same floor as a function of monitoring location. One sensor was usually placed halfway between the underside of the floor surface and the void ground; additional sensors were then located in line with this but closer to the joists and the void ground surface itself and, if different access points were possible, sensors could also be placed in other void locations based on the same principles. These variables were then used as a proxy for fungal growth risks (see section 5.2). In addition to the above monitoring, and where access was possible to the floor void, a visual and physical diagnostic building inspection was undertaken by accessing the floor void at different stages to ascertain any evidence of mould growth or timber rot.

Study limitations

Data collection was constrained by access to the floor voids, often only possible through one loose floorboard. This limited standardisation of sensor locations constrained data collection and visual and physical floor inspection to a small area of a large floor void. The monitored void locations and points of visual inspection may therefore not be considered to be representative of the floor void conditions elsewhere in the same floor void; and consequently neither of the associated mould risk. Moisture source strengths could not be quantified; for practical, access and resource reasons, this would have required a prohibitively large number of sensors in each floor to monitor variables at high resolution, such as soil moisture content in the void and externally; ventilation rates; material moisture content etc. (see e.g. Kurnitski (2000a), Airaksinen M. (2003)). However, moisture sources clearly affect the void conditions and potential risks associated with energy-saving measures (see e.g. Matilainen (2003), Vanhoutteghem (2017) and Kurnitski (2001)). Moisture source strength hence remains a source of uncertainty, likely contributing to the variation in observed void conditions in the floor sample.

Additionally, the large number of different variables in the sample limits interpretation of differences in floor void conditions between floors; especially the intentional inclusion of 'problem' floors limits comparison between insulated and uninsulated floor void conditions. In several floors only short-term monitoring was possible; but this is not a good indicator of floor void conditions: as described in previous sections. Clearly, the short monitoring periods for certain floors in this study do not provide mould risk insights over all seasons e.g. monitoring over summer may overestimate mould growth risk, while monitoring over winter may underestimate the risk.

Additionally, due to practical and resource issues, this study monitored air temperatures and relative humidities, while most models use surface conditions to evaluate mould growth risk; this creates uncertainty about the use of air temperature conditions as a proxy for surface conditions. In this respect, Vereecken et al. (2015) mentioned the potential difference between air and surface relative humidity: an equilibrium between air and surface RH will, especially for short RH fluctuations, not be achieved, which can have an impact on the mould risk assessment. Additionally, (H. Altamirano-Medina, 2009) reported that surface RH may be 10% higher than surrounding air RH for internal room surfaces of new dwellings; however the impact for floor voids is unknown. The difference between surface and air conditions will be largest for the uninsulated floors, because the addition of insulation in insulated floors reduces the relative impact on void conditions of the house interior, compared to the surfaces within the void (see e.g. Airaksinen M. (2003)). The difference will depend on several factors such as the room temperature, the insulation’s thermal performance, the presence of a ground cover, etc. and will be location dependent, which again requires spatial monitoring to enable a thorough surface temperature mapping. The difficulty of the determination of the surface conditions is clear from the use of air conditions instead of surface conditions in other crawl-space studies (e.g. Laukkarinen and Vinha (2017), Kurnitski (2000a), Airaksinen M. (2003); Matilainen (2003) and Flynn (1994)); the complication of measuring ground surface temperatures and RH is noted by e.g. Kurnitski (2000b).
Finally, handheld two-pin wood moisture content (WMC) meters were initially used (after e.g. Stiles (1994)); however, depending on the timber, its treatment and prior exposure to damp, as well as how deep and whether measured in the grain or against the grain, a significantly different WMC was obtained for the same joist location (see also e.g. Straube (2002), outside the instrument accuracy and across different thresholds, which made the interpretation of results unreliable, they are not included here.

5.2. Hygrothermal conditions in uninsulated and insulated voids: Results and discussion

Analysis of yearly temperature and RH conditions

Tables 3 and 4 present the mean RH and void temperatures for all the sensors combined per floor void for the uninsulated and insulated floors, respectively. Additionally, these conditions are compared to some of the isopleth thresholds presented in section 3.2.1 to evaluate potential mould growth risk. In this comparison, the longest period of consecutive threshold exceedance (in hours) is indicated. If no exceedance of the threshold takes place, this is indicated by a green colour in Tables 3 and 4. If the threshold is exceeded for a period of less than 30 consecutive days, this is indicated in orange, while a red colour indicates that the threshold is exceeded for at least 30 consecutive days. As previously described, mould growth tends to occur at lower moisture thresholds and is a precursor of wood-rotting fungi, which require higher moisture requirements. Hence evaluating floor void conditions based on the risk of mould growth contamination minimises adverse occupant health impacts from possible fungal spore transfer to living spaces, while simultaneously also reducing risk of structural damage caused by wood-rotting fungi. Mould growth risk has also been used by most research in this area to evaluate a construction's condition (Airaksinen, 2003, Hukka, 1999, Viitanen et al., 2010, Sedlbauer, n.d., Johansson, 2012).

The uninsulated floors were slightly warmer on average than insulated floors (i.e. five of the nine uninsulated floors had a mean temperature of 16ºC or 17ºC), given that they were conditioned by heat loss from above. While both insulated and uninsulated samples have a mean void temperature of approximately 15ºC, eight of the nine insulated floor void conditions had void temperatures ≤15ºC. This lower void temperature for insulated floor voids becomes even more clear when focusing on the measurements during winter only, resulting in a lowest mean temperature of 9.9°C for the insulated floor voids and 11.8°C for the uninsulated floor voids (not explicitly mentioned in Tables 3 and 4). The mean temperatures during winter for all the insulated floor voids was 12.9°C, compared to 13.3° for the uninsulated floor voids, where the former value was influenced by the bead-filled floors (Floor 11 and Floor 15) and the shorter (and warmer) winter period measurement on Floor 13 (when excluding Floor 11, 13 and 15, the value of 12.9°C is reduced to 12.0°C). Due to the colder void conditions as well as self-selected sample of 'historically damp' floors in the insulated floor sample, it is unsurprising that the mean RH in these insulated floor voids ranges between 73% to 93% over their monitored periods, which is more humid than the uninsulated floors with a mean RH between 66% and 94%. High RH conditions were observed in Floor 1 and 9; Floor 1 had a rainwater pipe leak and water ingress into the floor void during the monitoring period; Floor 9 had blocked ventilation paths, which may explain moisture build-up. Note that the moisture issues in Floor 1 occurred in the final 12 months of a 3 year monitoring period, highlighting the dynamic nature of floor void conditions, and their interaction with whole house mechanisms. Excluding 'damp' Floors 1 and 9 in the uninsulated sample leads to reduced RH ranges between 66 and 79%. As previously described, the differences between floors and insulated/uninsulated floor void conditions might be due to sampling strategy and do not constitute evidence of insulated floors being subject to increased moisture risk. Furthermore, the floors were monitored over different seasons, which also impedes a clear comparison.

Comparison of the uninsulated and insulated floor void sample with other existing UK floor void data is not possible due to the absence of such data; comparison with the Nordic sample of insulated floor voids indicates that the ranges observed here for the entire sample (13ºC to 18ºC and 66% to 94% RH on average**)** are within the ranges in Table 1, which indicates a relative humidity ranging from 50% to 95%, depending on source and void characteristics and monitoring season. As expected, Finnish floor voids have lower minimum temperatures due to the colder climate (and inclusion of mainly insulated floors). As indicated in Tables 3 and 4, the mean individual sensor readings are similar for uninsulated and insulated floors and slightly elevated compared to the Nordic floor sample (Table 1). Given the difference in climatic and constructional characteristics, no robust conclusions can be drawn from this. Clearly, further monitoring in more floor voids is required to establish if these trends are also observed in the wider stock.

Evaluating the potential mould growth from the observed RH and temperature-conditions based on some of the critical thresholds presented in section 3.2.1, indicates that the choice of mould risk evaluation criterion has an important impact on the results. The lowest isopleth for the hazardous class B/C (LIM B/C) indicates a possible mould growth risk starting from lower RH levels (see Figure 7) and thus results in a higher mould growth risk compared to the other thresholds. Also based on the other thresholds in combination with a critical exposure time of 30 days, several floors are found to include a mould growth risk (indicated by the red color in Table 3 and 4). Here, the critical exposure time of 30 days is an assumption made based on criteria for indoor spaces (IEA, 1990) and on the distance between Sedlbauers' LIM and his other isopleth curves, indicating the mould growth initiation after 1, 2, 4, 8 and 16 days. Despite the prediction of a mould growth risk for some of the floors, in practice only in one case of the seven visually inspected floor voids (Floor 1) was mould growth observed; though this was attributed to a leaking pipe (see Figure 4). Floors 11, 13, 14 and 15 were a purposively-selected sample due to homeowner concern about dampness history. The floor void conditions in floors 13, 14 and 15 suggest that dampness issues may still be a problem. For Floor 11, the predicted risk seems to largely depend on the location in the floor. Apart from these floors, comparison with the selected thresholds also suggests potential mould growth risk in the insulated Floors 6, 8, 9, 10 and 12; mould growth was not visually observed during data collection periods, however this does not mean there was no microscopic growth or that no mould growth took place during periods without visual observations. Finally, as with the RH and temperature conditions, the monitoring and inspection interval and period can have an impact on the predicted mould risk indicated in Table 3 and 4. A short measurement period (e.g. for the uninsulated Floor 6) or sampling during winter (e.g. uninsulated Floor 6 and some locations in the insulated Floor 6) could result in an under (or over-) estimation of the mould growth risk. A closer look at the seasonal variability is given in the next section.

	Visual mould growth	Sensor	RH_{mean}	T_{mean}	Total days (excl. NaN)	Season	Longest period of consecutive threshold exceedance (h)				
			(%)	(°C)			LIM B/C	LIM I	LIM II	RH_{crit} VTT	80%
UNINSULATED FLOOR SAMPLES											
Floor 1	yes	1	82	13	132	W, SP, SU, A	977	758	742	742	742
		2	72	15	633	W, SP, SU, A	2738	1203	1170	1181	1204
		3	94	15	791	W, SP, SU, A	16236	14893	13359	14367	15687
		4	91	12	138	W, SP, A	1801	1577	1151	1527	1577
		5	98	12	138	W, SP, A	3309	1585	958	1528	3309
		6	94	12	138	W, SP, A	1511	989	958	958	2378
		7	89	11	98	W, SP, A	2351	1554	490	788	2350
		MEAN	*89*	*13*							
Floor 2	no	8	69	17	726	W, SP, SU, A	1058	259	106	77	115
		MEAN	69	17							
Floor 3	n/a	9	66	17	520	W, SP, SU, A	462	183	64	49	80
		MEAN	*66*	*17*							
Floor 4	no	10	74	16	369	W, SP, SU, A	3596	1603	479	367	515
		11	72	16	369	W, SP, SU, A	3556	1419	467	144	476
		12	74	17	262	W, SP, SU, A	3593	2023	811	838	838
		13	74	16	369	W, SP, SU, A	3685	695	440	246	462
		MEAN	*74*	*16*							
Floor 5	n/a	14	83	18	151	SP, SU, A	3617	1847	1622	1619	1619
		15	73	19	151	SP, SU, A	425	138	62	60	60
		16	79	15	151	SP, SU, A	1110	687	360	0	362
		17	80	15	151	SP, SU, A	711	447	357	0	359
		MEAN	*79*	*17*							
Floor 6	no	20	77	9	13	W	96	29	7	0	30
		21	72	10	13	W	35	15	0	0	13
		22	62	13	13	W	0	0	0	0	0
		23	78	13	6	W	99	20	8	0	13
		24	74	13	6	W	81	10	3	0	10
		25	67	14	6	W	0	0	0	0	0
		MEAN	*72*	*12*							
Floor 7	no	37	72	15	343	W, SP, SU, A	326	178	90	10	144
		38	72	13	118	W, SP	125	0	0	0	0
		39	72	12	107	W, SP	66	0	0	0	0
		MEAN	*72*	*13*							
Floor 8	n/a	40	73	16	25	SU, A	121	63	7	0	18
		41	72	16	25	SU, A	123	64	14	0	19
		MEAN	*72*	*16*							
Floor 9	n/a	44	94	14	117	SU, A	2819	2819	1397	1779	1780
		MEAN	*94*	*14*							

Table 3. Mean void RH and temperature for all the sensors in the uninsulated floors, combined per floor and

comparison to the critical thresholds according to a selection of (lowest) isopleths for mould growth (see Figure 7). Additionally, a constant RH of 80% is applied as a threshold. Green is assigned if no exceedance of the threshold takes place, orange if the threshold is exceeded for a period less than 30 consecutive days; and red if the threshold is exceeded for at least 30 consecutive days. Additionally, for each sensor the longest period of consecutive threshold exceedance is indicated (in hours). As the length of the measurement period and the sampled season can have an impact on the predicted mould risk, also the total experimental time (with exclusion of NaN-values) and the sampled seasons are indicated (W = Winter, SP = Spring, SU = Summer, A = Autumn). The mean temperature of all insulated floors was 15ºC, the mean relative humidity was 76% RH.

	Visual mould growth	Sensor	RH_{mean} (%)	T_{mean} (°C)	Total days (excl. NaN)	Season	Longest period of consecutive threshold exceedance (h)				
							LIM B/C	LIM I	LIM II	RH_{crit} VTT	80%
INSULATED FLOOR SAMPLES											
Floor 6	no	26	82	10	480	W	480	278	1	0	315
		27	76	12	480	W	378	1	0	0	1
		28	73	12	480	W	20	0	0	0	0
		29	77	10	552	W	68	38	17	0	65
		30	73	10	552	W	32	17	10	0	18
		31	69	12	552	W	11	0	0	0	0
		32	76	13	122	W	59	10	0	0	0
		33	76	12	122	W	97	0	0	0	0
		34	73	13	122	W	7	0	0	0	0
		35	79	15	5543	(W), SP, SU, A	523	258	157	42	175
		36	81	16	5543	(W), SP, SU, A	3010	2282	644	728	728
		MEAN	*76*	*12*							
Floor 8	n/a	42	71	12	5166	W, SP, SU, A	494	106	47	0	51
		43	76	14	9912	W, SP, SU, A	3443	858	278	0	329
		MEAN	*74*	*13*							
Floor 9	n/a	45	81	15	2819	SU, A	1468	695	260	0	315
		MEAN	*81*	*15*							
Floor 10	no	46	84	15	2413	W, A	2413	1973	1189	1891	1891
		47	82	15	3619	W, A	3619	2046	1493	1954	1955
		MEAN	*83*	*15*							
Floor 11	n/a	48	89	15	13825	W, SP, SU, A	11776	9392	4329	6517	6517
		49	76	16	17101	W, SP, SU, A	3712	1698	1275	1397	1398
		50	66	17	3618	W, SP, SU, A	516	60	0	0	0
		51	66	19	5038	W, SP, SU, A	301	90	0	0	0
		52	66	18	10124	W, SP, SU, A	717	169	11	0	19
		53	73	15	5086	W, SP, SU, A	728	693	119	0	136
		54	75	17	5086	W, SP, SU, A	1902	356	32	0	43
		MEAN	*73*	*17*							
Floor 12	no	55	81	14	6359	W, SP, SU, A	760	344	229	0	318
		MEAN	*81*	*14*							
Floor 13	n/a	56	84	16	1177	W, SP	1177	1177	958	1001	1001
		57	98	15	1177	W, SP	1177	1177	1177	1177	1177
		58	97	14	1177	W, SP	1177	1177	1177	1177	1177
		MEAN	*93*	*15*							
Floor 14	no	59	86	14	11764	W, SP, SU, A	8803	4710	1097	1204	1225
		MEAN	*86*	*14*							
Floor 15	n/a	60	86	16	5700	W, SP, SU, A	3707	3030	2986	2996	2998
		61	94	14	5699	W, SP, SU, A	5699	5699	3884	5699	5699
		MEAN	90	15							

Table 4. Mean void RH and temperature for all the sensors in the insulated floors, combined per floor and comparison to the critical thresholds according to a selection of (lowest) isopleths for mould growth (see Figure 7). Additionally, a constant RH of 80% is applied as a threshold. Green is assigned if no exceedance of the threshold takes place, orange if the threshold is exceeded for a period less than 30 consecutive days; and red if the threshold is exceeded for at least 30 consecutive days. Additionally, for each sensor the longest period of consecutive threshold exceedance is

indicated (in hours). As the length of the measurement period and the sampled season can have an impact on the predicted mould risk, also the total experimental time (with exclusion of NaN-values) and the sampled seasons are indicated (W = Winter, SP = Spring, SU = Summer, A = Autumn). The mean temperature of all insulated floors was 15ºC, the mean relative humidity was 82% RH.

Seasonal analysis

Four uninsulated floors and three insulated floors were measured for at least 12 months. As an example, Figure 10 and 11 show the seasonal void RH and temperature for some locations in these uninsulated and insulated floors. In general and as reported elsewhere, floor voids were warmer and had higher RH in summer (21st June to 21st September) than in winter (21st December to 21st March), and this was the case for both insulated and uninsulated floor voids (see also Table 5 and 6). An exception to this is uninsulated Floor 1, which has higher RH in autumn and in winter than in summer, likely due to a rainwater pipe leakage in the last year of monitoring, which led to moisture build up over time and mould growth on the brick foundation wall - see Figure 4. For the insulated floors (Figure 11, Table 6), void conditions have generally similar or lower RH during autumn than in summer, despite being colder. Exceptions to this are sensors 48 and 54 in Floor 11 (Table 6); the conditions in Floor 11 where measured in the bead filled void with sealed airbricks.

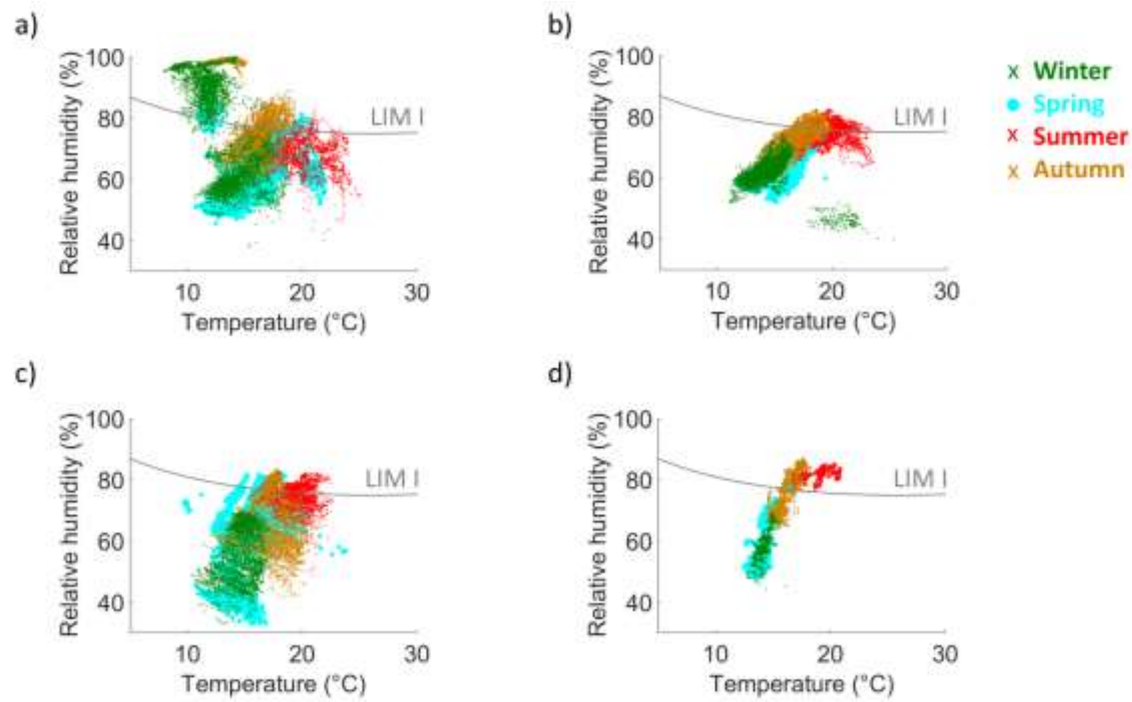

Figure 10: Seasonal void relative humidity and temperature for uninsulated floors: (a) Floor 1 (sensor 2), (b) Floor 2

(sensor 8), (c) Floor 3 (sensor 9), (d) Floor 4 (sensor 12). Additionally, the lowest isopleth for mould growth (LIM I) curve (Sedlbauer, 2001) is shown. With exception to Floor 1, the less optimal mould growth periods during winter (green) are clearly visible and below the LIM I curve.

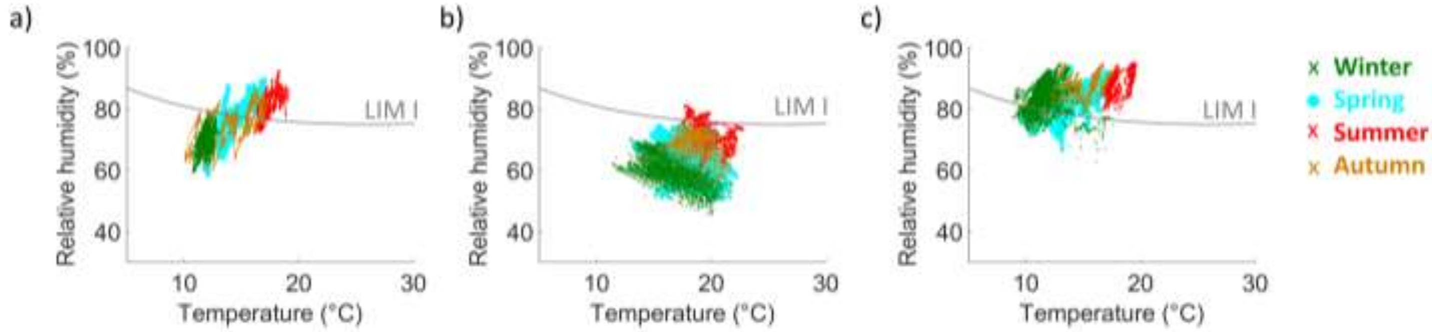

Figure 11: Seasonal void relative humidity and temperature for insulated floors: (a) Floor 8 (sensor 43), (b) Floor 11 (sensor 52), (c) Floor 14 (sensor 59). Additionally, the lowest isopleth for mould growth (LIM I) curve (Sedlbauer, 2001) is shown, with similar or lower RH during autumn than in summer, despite being colder in autumn; conditions in Floor 11 where measured in the bead filled void. In Floor 8 (a) and 11 (b), the less optimal mould growth periods during winter (green) are clearly visible and below the LIM I curve.

	Floor 1 Sensor 2		Floor 2 Sensor 8		Floor 3 Sensor 9		Floor 4 Mean all		Mean	
	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
Spring	16 (11-22)	64 (46-96)	16 (12-20)	65 (52-76)	16 (10-24)	66 (33-82)	15 (12-18)	66 (46-83)	16	65
Summer	20 (15-25)	69 (40-87)	19 (17-24)	75 (64-82)	19 (16-23)	74 (49-82)	19 (16-22)	81 (73-87)	19	75
Winter	13 (8-19)	76 (38-100)	15 (11-25)	62 (40-74)	15 (10-18)	55 (33-70)	14 (12-18)	66 (44-79)	14	65
Autumn	15 (11-19)	79 (55-100)	16 (12-20)	71 (57-82)	16 (11-22)	65 (42-84)	16 (13-20)	77 (62-88)	16	73
Yearly	16	72	17	68	17	65	16	73	16	69

Table 5: Mean seasonal void temperature and relative humidity for uninsulated floors with at least 1 year data (the seasonal minima and maxima are given between brackets). The data in red indicate where winter RH is larger than summer RH, caused by a rainwater pipe leak in Floor 1.

	Floor 8		Floor 11 (airbricks closed, bead filled void)										Floor 14		Mean	
	Sensor 43		Sensor 48		Sensor 52		Sensor 53		Sensor 54		Mean		Sensor 59			
	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
Spring	14 (12-17)	77 (58-90)	15 (11-18)	88 (67-93)	17 (13-22)	66 (50-75)	15 (13-19)	71 (61-77)	17 (16-19)	71 (60-77)	16	74	14 (10-18)	85 (67-94)	15	79
Summer	17 (16-19)	82 (72-93)	18 (15-20)	87 (69-97)	20 (17-23)	72 (59-81)	20 (19-21)	77 (68-80)	20 (19-24)	72 (62-73)	20	77	18 (17-20)	89 (79-95)	18	83
Winter	12 (11-13)	69 (59-78)	11 (9-16)	92 (81-97)	16 (11-22)	59 (45-70)	14 (9-19)	70 (59-78)	16 (14-19)	73 (62-81)	14	74	12 (9-18)	84 (63-95)	13	76
Autumn	14 (10-17)	75 (60-87)	14 (10-19)	91 (80-99)	18 (14-23)	68 (53-76)	17 (12-21)	77 (65-85)	18 (16-20)	77 (66-83)	17	78	15 (11-18)	88 (78-95)	15	80
Yearly	14	76	15	90	18	66	17	74	18	73	17	76	15	87	15	79

Table 6: Mean seasonal void temperature and relative humidity for insulated floors with at least 1 year data (the seasonal minima and maxima are given between brackets). The data in red indicate where winter RH is larger than summer RH; conditions in Floor 11 where measured in the bead filled void with sealed airbricks; and sensor 48 was located near the void ground near the external foundation wall; sensor 54 was near joist level, 1m away from the external wall.

Uninsulated floor void temperatures for the sample of floors in Table 5, measured by the different sensors, ranged (averaged over time) between 13ºC to 15ºC in winter and 19ºC to 20ºC in summer; while RH ranged between 55% and 76% in winter and 69% to 81% in summer. For insulated floors presented in Table 6, winter void temperatures measured by the different sensors, ranged (averaged over time) between 11ºC and 16ºC with RH between 59% and 92%. In summer, void temperatures increased to 17ºC to 20ºC, with RH between 72% to 89%.

Generally and over at least a year, uninsulated floor voids appear to have lower humidity void conditions compared to the insulated floor voids: the mean RH (69%) of the four uninsulated floors is 14% below the mean RH (79%) of the three insulated floors, while both groups have similar mean void temperatures of 15ºC (insulated) and 16ºC (uninsulated); the mean RH of the four uninsulated floors is elevated due to a pipe leakage in Floor 1. However, floors were purposively sampled to included cases with historical damp problems, and cases in which there was some concern about potential damp, so direct extrapolation to the wider stock isn't possible. Overall however, the void conditions were in similar ranges to those reported by others in Finland, e.g. Pasanen (2001), Airaksinen (2003), Kurnitski (2000b) and Samuelson (1994) in Sweden, indicating that optimal conditions for mould growth might exist, depending on exposure time. Clearly, further monitoring in a variety of floor voids is required to establish if these trends are also observed in the wider stock.

Effect of sealing airbricks in winter

The sealing of airbricks can lead to winter heat loss reduction as discussed by (Hill, 2005). Some research argued that sealing of airbricks might, furthermore, reduce summer RH (Rose, 1994, Samuelson, 1994, Lstiburek, 2004), though others argued that doing so would lead to increased moisture build-up in the floor void (Oliver, 1997). Floor 7 was monitored pre-post sealing of the airbricks, although for the sealed airbricks only winter conditions and a short period over spring were monitored, which is likely to underestimate any mould growth risk. Similar temperatures and RH profiles for each month were observed, with - as expected - slightly elevated void temperatures and RH with sealed airbricks: 12-13ºC and 70-73% RH for sealed airbricks compared to 11-12ºC and 66-67% RH for unsealed airbricks - see Table 7. The slightly increased RH is possibly linked to sealing of the airbricks; though, it might also indicate that airbricks are not the sole moisture ingress path and instead could be related to changing void conditions when external conditions changed; this is likely site dependent (e.g. high ground water, presence of ground covers etc.) and would need checking on a case-by-case basis. From this one case study floor, it does not appear that short-term airbrick sealing over winter, while slightly increasing the RH in this floor, would lead to excessive moisture build-up in this uninsulated floor void. Further research is required into long-term sealing of airbricks in a larger sample.

	Floor 7			
	Sensor 37 (airbricks open)		Sensor 38 (airbricks closed)	
	T (°C)	RH (%)	T (°C)	RH (%)
January	**11**	**67**	**13**	**72**
	(9-17)	*(51-76)*	*(11-16)*	*(59-78)*
February	**11**	**66**	**12**	**70**
	(9-14)	*(53-77)*	*(10-15)*	*(57-75)*
March	**12**	**66**	**13**	**73**
	(9-13)	*(56-77)*	*(12-15)*	*(63-76)*

Table 7. Mean RH and temperature for pre-post sealing of airbricks in Floor 7, uninsulated floor

Three insulated floors (11, 13 and 15) in the monitored sample had sealed airbricks for several years (1 to 5 years). The floor void conditions for Floor 13, monitored only over a short winter period are on average 93% RH and 15ºC (see also Table 4). For Floor 15, on average 90% RH and a temperature of 15ºC was measured. Hence, the relative humidity level in these 'sealed' floor voids seemed to be higher than average, and Floor 13 and 15 are, according to literature thresholds, at mould growth risk. Meanwhile Floor 11 on average was 73% RH and 17ºC; however lower down in the void, Floor 11 measures a mean RH of 89% and 15ºC; this is discussed further below. It is unknown if these void conditions are a consequence of airbrick sealing or other variables; for example floors 11 and 15 were bead-filled and had a pre-insulation history of damp and timber rot, which was rectified prior to bead-filling the void, but it is not known whether these problems reoccurred or whether other variables, besides insulation and airbrick sealing, affected the void conditions. Despite the limited sample, this is a potential cause for concern and highlights that interventions must be undertaken on a case by case basis. Furthermore, post intervention monitoring with wireless, internet enabled sensors, may be an inexpensive way to ascertain that void conditions are not worsened.

A final consideration is that, while air velocity between 0.5 to 1.5 m/s could encourage the release of fungal spores (Pasanen, 1991b), mould growth and timber rot require stable environments (Ridout, 2001). Sealing of the airbricks creates more stable conditions, potentially increasing the risk of mould growth but decreasing the risk of spore diffusion. Figure 13 illustrates the more stable RH and temperature conditions in Floor 8 with sealed airbricks; it also highlights that - as expected – temperature conditions are more stable, slightly higher and with lower RH further away from the airbricks compared to near the airbricks, for this uninsulated floor.

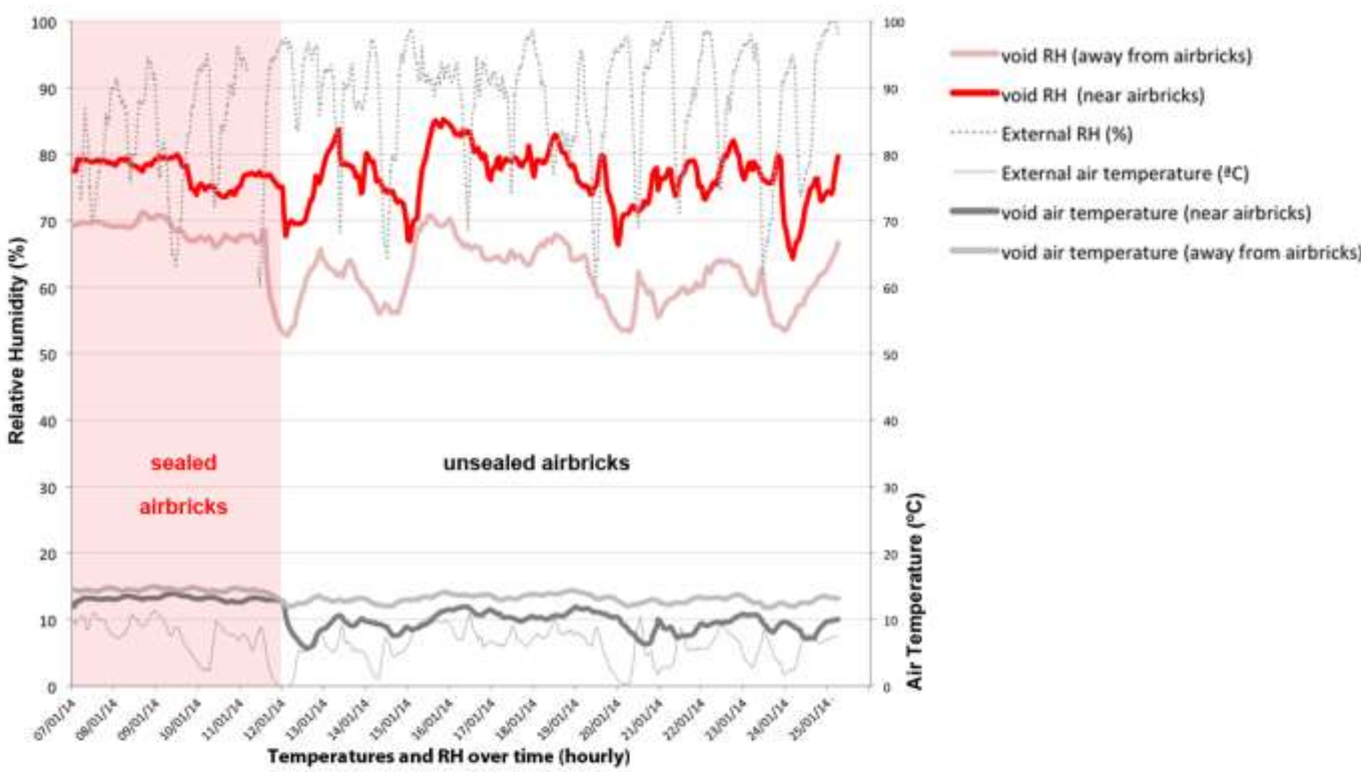

Figure 12. Impact of sealing airbricks on the dynamic behaviour of the relative humidity and temperature during a winter period in uninsulated Floor 8. Sealed airbricks result in more stable conditions; and further away from the airbricks might suggest higher RH when sealed for this floor. Away from the airbricks, the air temperature is higher, resulting in a lower air relative humidity.

Effect of location in the floor void

Sensors placed in different locations indicate that there are different conditions for different monitoring locations in the floor void. This is illustrated by for example insulated Floor 11 (Figure 13) which was measured in several different locations. There is an indication that some measured void conditions are below the LIM-curve in certain seasons (e.g. when measured near the floorboard surface), while others are very high (when measured near the bottom of the void – Figure 14). Note that Floor 11 sensors were suspended in a floor void fully filled with EPS beads and sealed airbricks. This floor also had a history of dampness, which was rectified prior to fitting floor insulation. Issues with localised monitoring and generalisation of localised data to an entire floor void are also highlighted in Table 3 and 4, where clearly different mould growth risks are predicted depending on the observed location.

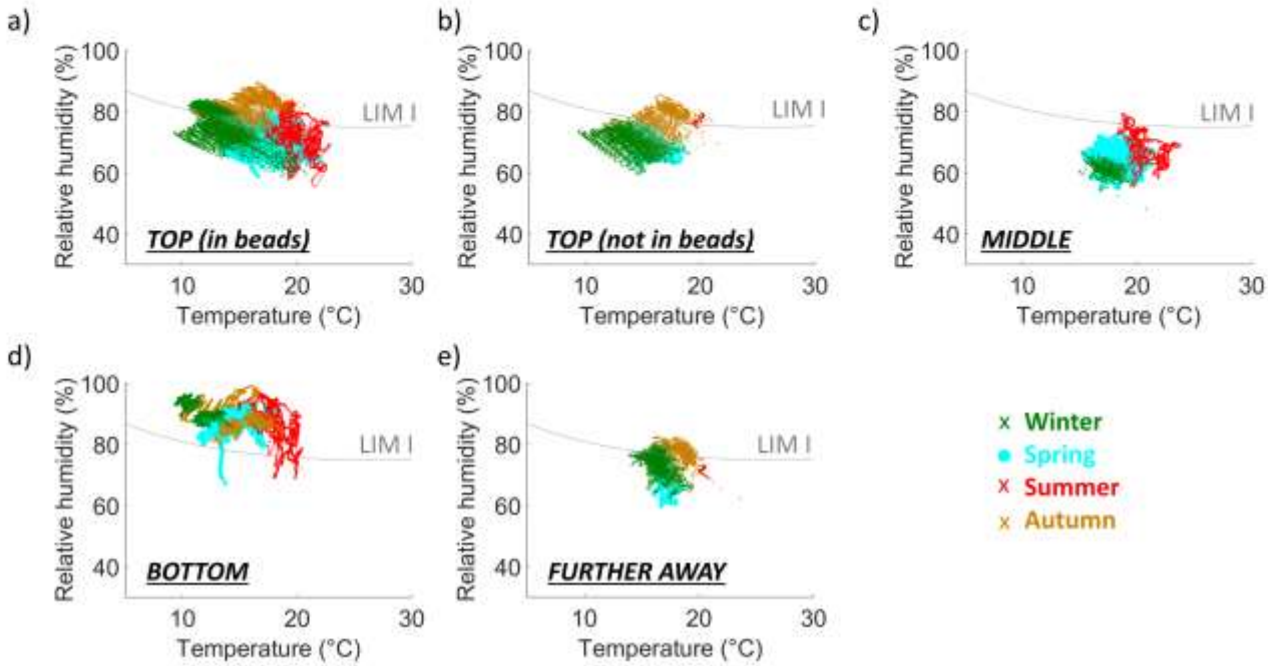

Figure 13: Seasonal void relative humidity and temperature for different locations in Floor 11, most of the sensors are placed near the external foundation wall due to access issues: (a) measured near top of joists, in beads (sensor 49), (b) measured at top of joists but not in beads (sensor 53), (c) measured 200mm below joists, in middle of bead-filled void (sensor 51), (d) measured 400mm below joists, near the bottom of the bead-filled void (sensor 48) and (e) measured about 1m away from the external wall at top of joists in beads (sensor 54). The lowest isopleth for mould growth (LIM I) curve (Sedlbauer, 2001) is shown, and indicates that some measured void conditions are below the LIM-curve in certain seasons, while others are very high (when measured near the bottom of the void) in all seasons.

Clearly, conditions in one location are not representative of conditions in other locations and the absence of mould growth in one location does not guarantee absence in other locations, hence monitoring should be undertaken at different locations and at different heights.

6. Conclusion and recommendations

The installation of floor insulation brings a potential for energy and carbon reductions, as well as an improvement to occupant thermal comfort. However, upgrading floors also changes floor void conditions, which might lead to moisture build-up and therefore to mould and fungal growth. These organisms can affect building structure or occupant health if mould spores transfer into living spaces above. Therefore, it is important to consider the global performance of the construction taking into account for example the pressure differences across the floor as well as the air flow and the ventilation rates in the floor voids. At present these considerations are poorly characterised, individually or combined.

Some evidence in climates with warm and humid summers suggests that mould growth risk may increase in insulated floors due to an increased RH in floor voids. However, generally floor voids are poorly characterised for different climates and constructions and it is unclear if increased risk of mould growth also applies to colder and drier climates.

Fifteen ground floor crawl spaces were monitored in England; six were uninsulated and nine were insulated; two floor voids were monitored for short periods pre-post insulation while another floor consisted of an insulated and uninsulated section. The uninsulated mean floor void air temperature was 15ºC with mean RH of 76%. As expected and on average, the uninsulated floors were slightly drier compared to the insulated floors (mean 82% RH of all nine floors). Most insulated floors in this sample meet or exceed the critical thresholds for mould growth for significant periods, as compared to the literature. However, one uninsulated floor had high void RH due to a rainwater pipe leak during the monitoring period; this was the only case where actual mould growth was visually observed during the monitoring period. Because cases were purposively sampled to explore different floor void conditions and study methods, ‘historically damp’ floors were intentionally included in the insulated floor sub-sample for this study. Additionally, monitoring occurred in different periods and for different lengths of time, hence a robust comparison between insulated and uninsulated floor void conditions was not possible and was not the purpose of this study.

From a sub-sample of seven floors for which seasonal data was available, it was generally observed that there were some seasonal differences in void conditions: for uninsulated floor voids, summer RH was generally higher than winter RH, while for insulated floor voids, summer and autumn RH were generally higher than in winter. Given the sampling strategy, the data did, however, not allow a fair comparison between insulated and uninsulated floors. Generally the closer to the airbricks, the greater the RH and the colder the void compared to further away from the airbricks, which also provided more stable conditions. The long-term effect of airbrick sealing could however not be verified and a longer-term study and a larger random sample would be required to do so.

The variability in void conditions across the sample, both pre- and post-insulation retrofitting, highlights the need for further research. For practical reasons, this paper did not measure or quantify moisture sources in the voids and their contribution to the void condition. However, site specific considerations, such as the level of the water table, the actual ventilation through the void, infiltration between void and living spaces, and condition of the ground beneath the floor are important factors to consider, in addition to the identification of faults such as leaking services and drainage. This variability also lead to highly inhomogeneous conditions within a single case study floor void, associated with the proximity to ventilation, sources and sinks of moisture. This suggests that high resolution monitoring (i.e. a large number of measurement points) is necessary to characterise the space well, for example at different heights, proximity to airbricks, joists, and sleeper walls. The absence or presence of conditions that could lead to mould growth in one location is not necessarily a good indicator of the conditions elsewhere. Characterisation of floor void conditions is best performed over a long monitoring campaign, to account for seasonal climatic factors, ideally at least one year in duration. Visual inspection provides a valuable supplement to such monitoring.

Criteria for mould growth risk instead of for fungal decay are recommended to use for evaluating floor void conditions due to the possible impact on occupant health. The UK floor void samples were evaluated based on a selection of lowest isopleth thresholds for mould growth and an 80% RH-rule. Except for the impact of the sampling location, also the choice of the mould growth evaluation criterion was shown to influence the predicted risk. Further research is required to define robust thresholds for the mould growth risk assessment in floor voids. In this respect, also further research on mould growth under fluctuating conditions is desirable. Such fluctuating conditions could, for instance, result in an interim drying out of the mould spores, something that is not taken into account in the isopleths. More sophisticated prediction models that can deal with a dynamic input can be found in the literature; though, these are not validated for typical floor void conditions, with the exception of the VTT-model. Moreover, previous studies (Vereecken and Roels, 2012, Vereecken et al., 2015, H. Altamirano-Medina, 2009) indicated mould growth predictions that were variant between models.

Encouraging the widespread uptake of insulation interventions in floors requires a body of evidence that such work will not cause occupant health issues or structural problems. This evidence does not yet exist, and such interventions should therefore be undertaken with great care. Equally at present there is insufficient evidence to indicate whether floor insulation will increase moisture build-up risk. Hence, when insulating floors, awareness of potential risk factors and minimising these risks in interventions (such as fixing any dampness problems prior to insulation, ensuring adequate ventilation to dissipate moisture build-up, considering the likely moisture conditions in the specific site etc.), should help manage risks. Additionally, regular post-retrofit inspection and monitoring would help detect any problems at the early stages and reduce long-term risk. Given that there are millions of properties with suspended timber ground floors globally, further research on the sources of moisture, and effective moisture source control measures, is required alongside the consequences of undertaking energy-efficiency measures in such floors. Clearly moisture sources (and any moisture source reduction measures) affect the moisture build-up risks and any risks associated with energy-saving interventions, such as insulation and ventilation changes through the void (and up into the spaces above). Hence more research is needed into these factors but also their interactions to gain a better understanding of risks of specific energy-efficiency interventions in floors with specific moisture source strengths, and with and without potential moisture reduction measures.

The recommendations on the research method for sampling, monitoring and evaluating floor void conditions, inferred from the findings of the UK floor void measurement campaign, are of major importance for the reliability of such further research. The exploratory nature of this study highlighted seasonal and spatial monitoring implications as well as practical data collection issues related to access to floor voids and their instrumentation, supporting reflection and refinement of methodologies for future studies. The study also highlighted that suspended ground floors are poorly characterised at present, indicating the need for a wider study to classify different floor archetypes and void conditions. Until this is done, the sampling of floors based on pre-set criteria when such criteria and its floors are not yet classified, will remain difficult. In addition, at present it is unknown if a sufficient number of floors with the same criteria (and exclusion of other criteria) can be accessed for monitoring. Despite these challenges, some methodological implications to optimise future studies, can be drawn out based on the current study:

- Each floor should be monitored at high resolution for minimum 1 year, both at different depths in the void and at different locations across the floor void; near airbricks and further away as well as near joists and floorboards as well as the void ground. This will require different access points, with sensors which can measure at the higher RH range (up to 100%).

- Due to access issues and the long-term monitoring campaign, ideally sensors are all wireless and internet enabled to collect data remotely. Some sensors are likely to become embedded in the insulation post-intervention so methods to retrieve sensors will be needed, or otherwise sacrificing instruments at the end of the study.
- Variables to monitor include void air temperatures and RH in different locations, as well as surface temperatures and RH in nearby locations and continuous WMC measurements. Ideally surface temperatures and conditions are measured instead of air temperatures as a proxy. In addition to this, some external and void soil moisture should be monitored in different locations and at different depths, along with void airflow and external wind speeds and direction at airbrick height.
- Ideally, access is obtained to a large sample of floors, randomly sampled to be statistically meaningful to compare insulated and uninsulated floors. However due to the difficulty in gaining access to such floors and the monitoring resources required, instead a random sample of uninsulated floors can be monitored at least 1 year pre- intervention and minimum 1 year post energy-efficiency measures.

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[i] The historic requirements appear sufficient given the lack of widespread timber rot reporting in the existing housing stock.

[ii] Xerophilic means tolerant of dry conditions