RESEARCH FUNDED THROUGH THE KEELE UNIVERSITY RESEARCH, INNOVATION AND SKILLS PARTNERSHIP (KRISP) PROJECT

Radiators and their relationship to indoor air quality issues

An evidence report for Rotarad Limited.

Luke Bellamy (BSc MRes MSc) & Nathan Wright (BEng)

2018

Keele UNIVERSITY

European Union
European Regional Development Fund

Abstract

Tasked with establishing the relationship between indoor air quality, the impact on human health and the accumulation of dust behind radiators, this report sets out to review the academic literature knowledge basis. This is to build a business case for Rotarad, based on current knowledge for the innovative radiator design and bracket mounting system which enables the radiator to swing away from the wall for access for cleaning and decorating.

No studies have been conducted investigating a relationship between indoor air quality, the impact on human health and the accumulation of dust behind radiators, and studies concerning dust contents fail to consider dust collection from behind radiators. This report is set out into three main sections looking at the academic literature, followed by two sections investigating real world consequences of this potential relationship.

The first three stages are broken down into the following sections: understanding how dust moves in a heated room, understanding the composition of dust, and understanding the health impact from dust in the home. The main findings of which are as follows:

- Dust movement in a room is influenced by radiators when operational, and those closest to the radiator have the greatest exposure to the dust particles carried by the thermal plume above the radiator.
- Dust contains a variety of different components including microbial taxa (fungi and bacteria), fiberous particles, skin, hair and other biological matter from occupants, industrial and household chemicals from cleaning, and particulates from cooking and other household activities, pollen, house dust mites, proteins from foodstuffs and plastics.
- Health impacts vary considerably, however the biggest impacts are on asthma incidence and allergic disease development. Impacts from particulate matter include cardiovascular disease. Whereas household chemicals and plastics could include a variety of impacts including brain and nervous system, lung and respiratory system, liver and digestive system, immune system, cancers, development/birth defects, hormone system and fertility and reproductive systems. These health impacts will vary based on the content of the dust, prevalence of the content in the dust, exposure route, exposure time, susceptibility of occupant and other factors.

For stage four, this report investigates hospital admission figures for asthma, describing the general trends of emergency admission data recorded between 2006 and 2016. The financial burden of asthma was also investigated in this section along with mortality rates associated with the illness. The main findings of this stage show:

- A consistent peak of emergency hospital admissions in September, the most commonly accepted reasoning for this peak is due to children returning to school after the summer holidays which exposes children to an increased number allergens.
- Approximately 1000 – 1200 asthma sufferers die each year in the UK alone, this equates to an average of 3 deaths per day.

- The total cost of asthma treatment to the NHS is approximately £1.1 Billion, with 60% of this being spent on pharmaceuticals to treat the illness.

For stage five, this report highlights current cleaning regimes that are in use within hospitals. The main findings of this stage show:

- Hospitals currently acknowledge that radiators are a potential haven for pathogens and bacteria. This is evidenced through numerous hospital cleaning guidelines having clearly defined methods and regimes to follow when cleaning radiators.
- Radiators are classed as a non-critical area in relation to cleaning, yet they are one of the only non-critical areas which have an inaccessible section which can allow dust accumulation.
- Studies have linked radiators being used after a long period of inactivity and the spread of bacteria.

A final section was added which highlighted other areas of interest. These included Sudden Infant Death Syndrome (SIDS), dust mites, pet dander and areas which should be considered. The main findings of this stage show:

- That indoor air quality may be linked with SIDS, but further research is required in order to confirm this relationship.
- Concentrations of dust mite allergens present in the air are influenced by not only dust, but also by ventilation and disturbance of the area.

Acknowledgements

We would like to thank the following people for the support in providing this fantastic opportunity, providing the funding and in constructing this important report for Rotarad, supporting their business aims and providing the opportunity to do industry based research.

Firstly we would like to thank Jayne Eagles for her advice, guidance and encouragement throughout this project; and also the Keele University KRISP Project for their provision of this project in collaboration with Rotarad and providing the funding. The funding through Keele University from the EU regional development fund made this project possible.

We would like to thank Malcolm and Caroline from Rotarad for collaborating with Keele on this project and being on hand to support any queries and providing us with this opportunity.

We would also like to thank James Franklin for his research and initial contribution to sections four and five of this report, and to David Watson for overseeing this project and being on hand for academic support and advice when required.

List of Figures

Contents

Introduction

Rotarad are a company with a unique bracket and mount system that enables the radiator to swing away from the wall along a horizontal axis at the base of the radiator at its mount, allowing access to behind the radiator for cleaning & decorating, as seen in Figure 1 below.

Figure 1. Example of Rotarad bracket and mount system which allows radiator to swing away from wall for cleaning and decorating access.

Rotarad approached Keele University to have a literature review survey carried out to understand what the research says about what the health implications for occupants from accumulated dust behind radiators in residential, national and commercial buildings.

No relationship with radiators and dust movement on human health has been discussed in the literature. Communication with academics confirms a lack of consideration/awareness. Because of this; making the case for a relationship between the dust behind radiators and the health implications, is a challenge. For this, the review had to be broken down into parts, with the literature at each stage reviewed to ensure what the current standard of knowledge is. This literature study, which will be discussed in the following chapters, was broken down into five main parts in order to make a case for Rotarad that there is literature supporting the hypothesis that dust from behind radiators has health implications for the occupants.

These five stages are as follows:

1. Understanding how radiators influence the air movement around a room, and how the dust particles are carried in that air.

Demonstrating that the radiators are an important influencer of air movement in a room and that it carries dust particles is intuitive to consider, but vital to demonstrate, as there may be other factors affecting the relationship between dust and air flow in indoor environments. Particularly in the context of tightening home thermal efficiency regulations that air changes in homes occur less often.

2. Understanding what is in dust and where those components have come from.

Familiarity with the current status of academic knowledge around dust contents, how dust in the home has been sampled, and what the sources of this dust in the home are, is an important step for the next stage of research.

3. Understanding the health implications from the exposure to household dust.

There are a number of complex health risks in our environment, and the role that dust could play and the potential implications is important to understand to ensure that, if it can be demonstrated that radiators influence the movement of dust around a room and that the content of the dust has health implications through inhalation (and potentially other) mechanisms, this builds up a case for Rotarad that their product can help solve these issues.

4. Investigating what the hospital admissions figures for highlighted health conditions and what connections can be made to dust implications.

Although building up a theoretical case would provide a basis for further study, looking at current hospital admissions figures now for the health risks identified for dust exposure, can help build a case that the dust may be a contributory factor to these hospital admissions. Although the hospital admissions may be triggered by other factors, these will be highlighted and dust triggers justified where possible.

5. Investigating case studies and problems with deep cleaning behind radiators in hospitals.

Having identified the dust contents and health implications for behind radiators, particularly in hospital settings, looking into what the standards are for cleanliness in hospitals with regards to radiators and problems hospitals encounter, helps build a financial business model for Rotarad.

Figure 2 below highlights the five stages of this document that this literature review project has set out to achieve, in order to make and academically support the Rotarad business case.

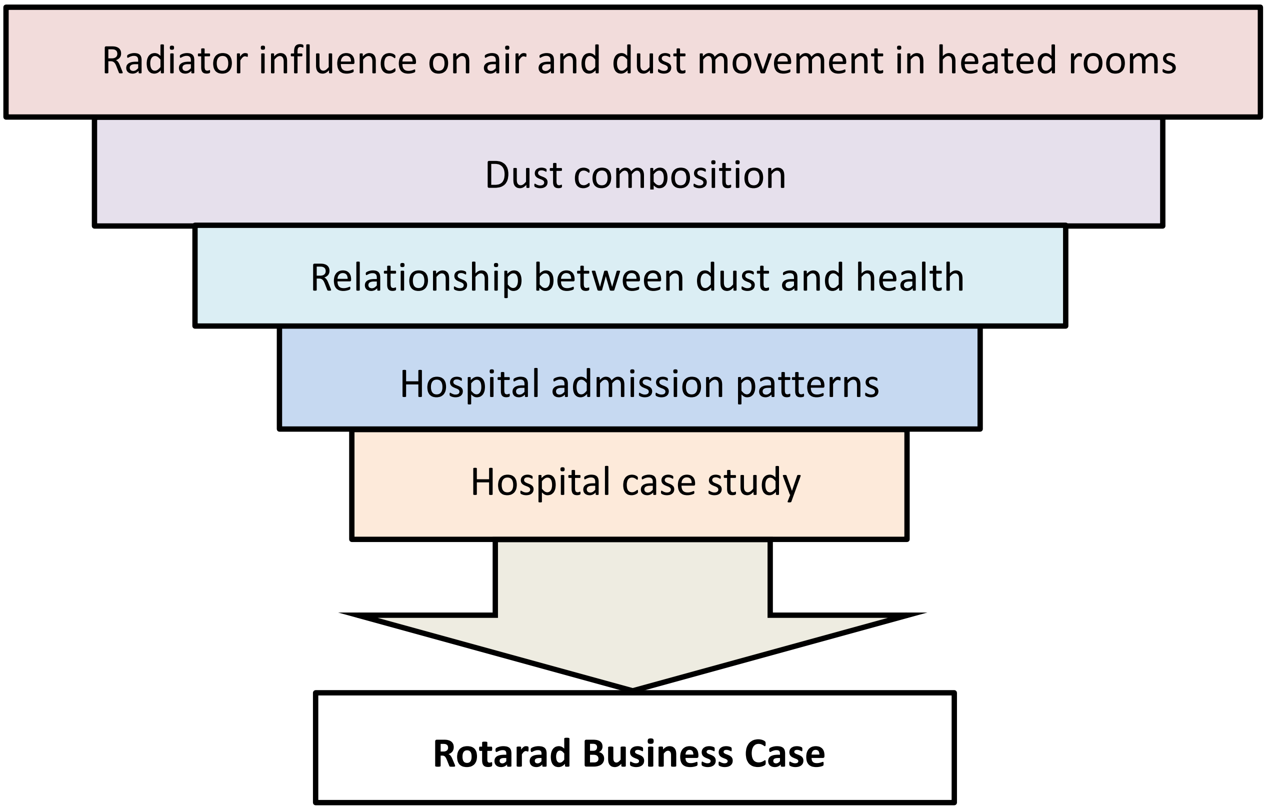


Figure 2. Table showing the staged literature review stages for the Rotarad business case.

Stage 1: Understanding how radiators influence the air movement around a room, and how the dust particles are carried in that air.

Behaviour of air and air particles in the room

One study by Bulińska *et al.* (2014) looks specifically at radiator influence of air movement around a room using Computational Fluid Dynamics (CFD) model. Although the air studied specifically looked at carbon dioxide, the findings of this paper help to build the academic case that radiators are the main influencer of air movement in a room. This paper demonstrates that the radiator surfaces heat the air up in the room and the window surface cools the air down, creating air convection current in the room. Furthermore, a comparison between carbon dioxide concentrations for the room with the radiator on vs off, demonstrates that when radiators are on, CO_2 concentrations both in vertical and horizontal plane are greater distributed around the room, whereas when they are off they are closer to the production source.

Although this study by Bulińska *et al.* (2014) does not consider the movement of dust, Lu *et al.* (1997) conducted a CFD model looking at particle and air movement around a room, findings that air movement and particle movement is complex. Figure 3 below highlights this complexity of air movement in a room, with the author highlighting that the area close to the heat source located below area (A), imposes a higher risk of exposure of particles to the occupants in that area of the room.

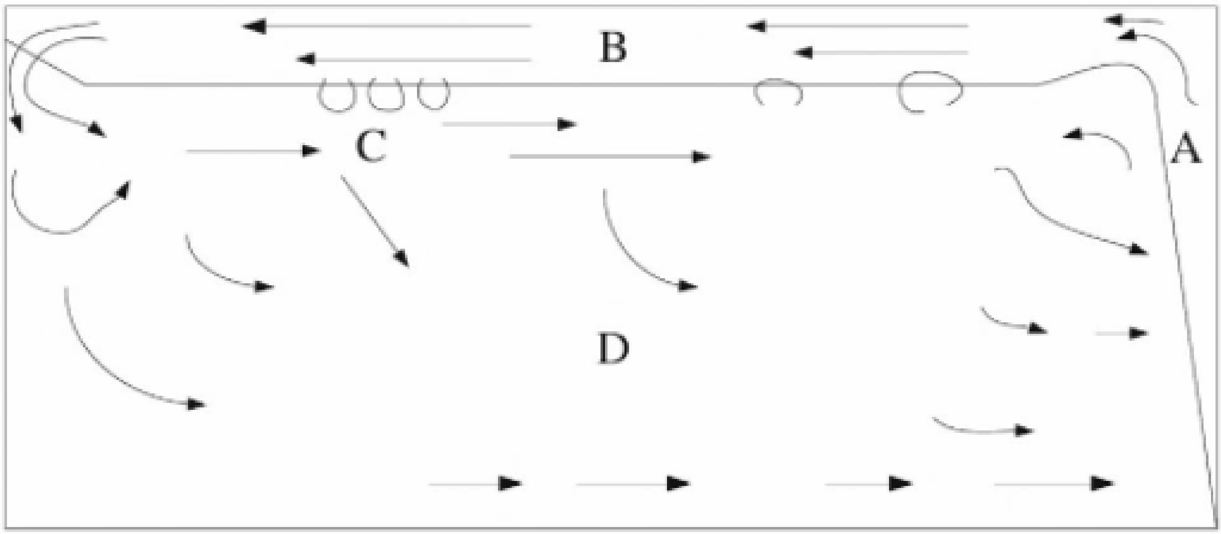


Figure 3. Observed air flow patterns in a room (Lu *et al.* 1997).

It can be seen in Figure 3 above, and more clearly in Figure 4, that the thermal air plume created by a radiator greatly influences the airflow pattern, temperature and pollutant particle distribution in the heated room (Lu *et al.* 1997; Chen *et al.* 2012; Wang *et al.* 2017).

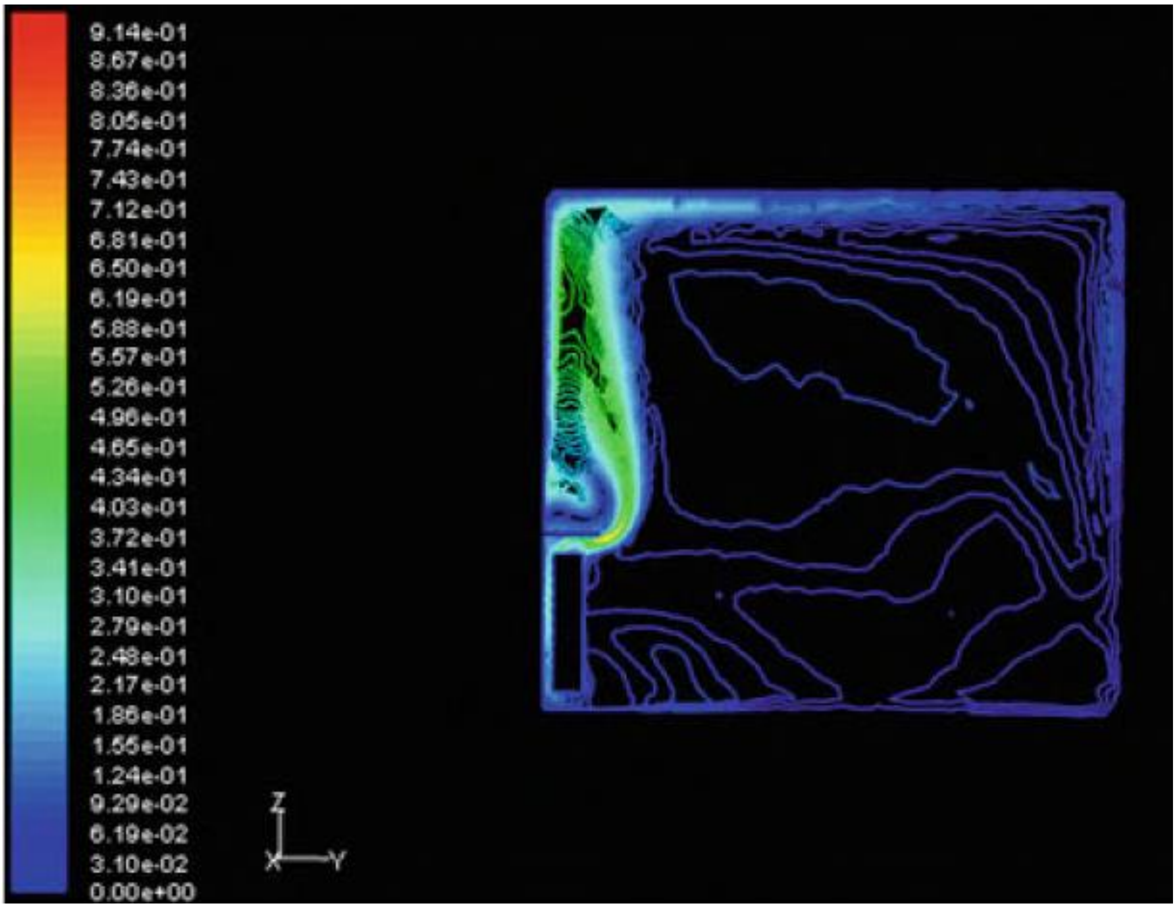


Figure 4. Air velocity contour influenced by radiator in a room in m/s (Wang *et al.* 2017).

A rising convective hot air plume (A) flows upwards into the “buffer zone” (B and C) under the ceiling. The convective hot air plume develops from the convective thermal boundary layer along the radiator surface and entrains the cold air from the surroundings through the bottom of the radiator. The hot air plume flows upwards against the radiator wall and then deflects when it reaches the ceiling (A to B). The air movement under the ceiling surface is complex as it develops into a region called the “buffer zone” under the ceiling. Some of the hot air flows along the ceiling surface, and some disperses downwards due to heat exchange. A large air circulation is formed under the ceiling due to the mixing of hot and cold air. The main air flow direction in the occupied zone (C & then D), i.e. under the “buffer zone”, is towards the hot surface due to the entrainment of the jet. A downdraught flow is formed at the cold surface opposite to the radiator. The air then disperses downwards into the core (D) of the room, to be subsequently entrained into the rising boundary layer, so completing its circulation. The thermal wall jet also affects the particle movement in the room space. Small particles are likely to suspend in the upper warm zone or deposit on the high level of internal surfaces; while large particles travel through the room space and deposit on the floor level (Lu *et al.* 1997).

Wang *et al.* (2017), building on the work by Lu *et al.* (1997), contributes by explaining that because the temperature of the air near the radiator is higher, there will be a large amount of dust particles accumulated near the radiator. When a large amount of contaminant particles accumulate on the wall near the radiator the distribution of the dust is deposited in strips. This is in line with the airflow characteristics above the radiator. However, the local speed drop caused by the air vortex can result in uneven settlement of the contaminant particles on the wall. Faster air flow speeds increase formation and distribution of dusts around the radiator. Local speed drops from air vortex results in uneven settlement of dust on wall behind radiator. Dust formation above the radiator was greatly hindered by placement of a baffle above the radiator as air flow was hindered upwards from the radiator (Wang *et al.* 2017).

Chen *et al.* (2012) looks at the impact that near-wall heat sources have on particle deposition. Chen *et al.* (2012) finds that the velocity of the air plume above the radiator increases with higher radiator temperatures, and is slower to decay. This is also true for a smaller gap between the radiator and the wall. For particle sizes in the range 2.5 µm–10.0 µm, a higher heat source temperature and a larger gap between the heat source and the wall have a positive effect on particle deposition. The following locations for particle deposition were highlighted:

- Ceiling - particle deposition is enhanced with higher heat source temperatures, and reduced with an increasing gap between the radiator and the wall.
- Floor - particle deposition for larger particles (>5.0 µm) decrease and for smaller particles (<5.0 µm) increase as the heat source temperature is increased. For most of the particle sizes, the deposition numbers increase with the increasing of the gap between the heat source and the near wall.
- Near wall - particle deposition increases with the heat source temperature. Particle deposition numbers are slightly higher in cases with a smaller gap between the heat source and the near wall for most particle sizes.
- Other walls – particle deposition is increased with an increasing of the gap between the heat source and the near wall and with an increase in temperature.

Although particle movement is aided by radiators, the research by Chen *et al.* (2012) highlights that in most cases, if the temperature of the room is increased past a certain point, larger particles in particular are more likely to be deposited on a surface in the room, and exposure to occupants might be greatest between certain radiator and room temperatures (Chen *et al.* 2012). Small particles are more likely to suspend in the upper warm zone of the room, depositing on high level internal surfaces (e.g. tops of doors), while larger particles travel through the room space and deposit on the floor (Golkarfard & Talebizadeh 2014).

Two heating systems compared for dust movement

Golkarfard & Talebizadeh (2014) has modelled the deposition of dust in a room with a radiator heating system and floor heating on the deposition of dust particles using a CFD model. This modelling demonstrates that particles from floor heating systems deposit particles more rapidly and are airborne for less time compared to a radiator heating system. This modelling shows that floor heating systems are capable of reducing room particle density down to near zero (Figure 6) and reaching near 100% particle deposition (Figure 7) by approximately 80 seconds. In comparison, radiator heating systems are unable to match the performance of floor heating systems, and by 200 seconds have not reached zero particle density or 100% particle deposition. This means that particles from radiator heating systems are suspended in the air for longer, and less likely to deposit. Figure 5 demonstrates this showing the location of particle deposition. Although radiator systems are more likely than floor heating systems to deposit on the floor, and to a lesser extent the walls, in total, fewer particles are deposited on any surface after 200 seconds.

Figure 8 shows the air velocity contours of the different heating systems, with the fastest air movement for radiator heating systems concentrated along one wall, whilst the floor heating system has faster air speeds more centrally in the room, creating highly different environments for particle movement.

Figure 9/Figure 10 demonstrates these two systems in action with dust movement, visualising what has been explained in previous figures. Dust movement for the radiator heating system is concentrated through the radiator, whereas in the floor heating system is more uniform early on in the model, and enables the air particles to settle quicker, with 200 second snapshot showing particles still present in the air for a radiator heating system.

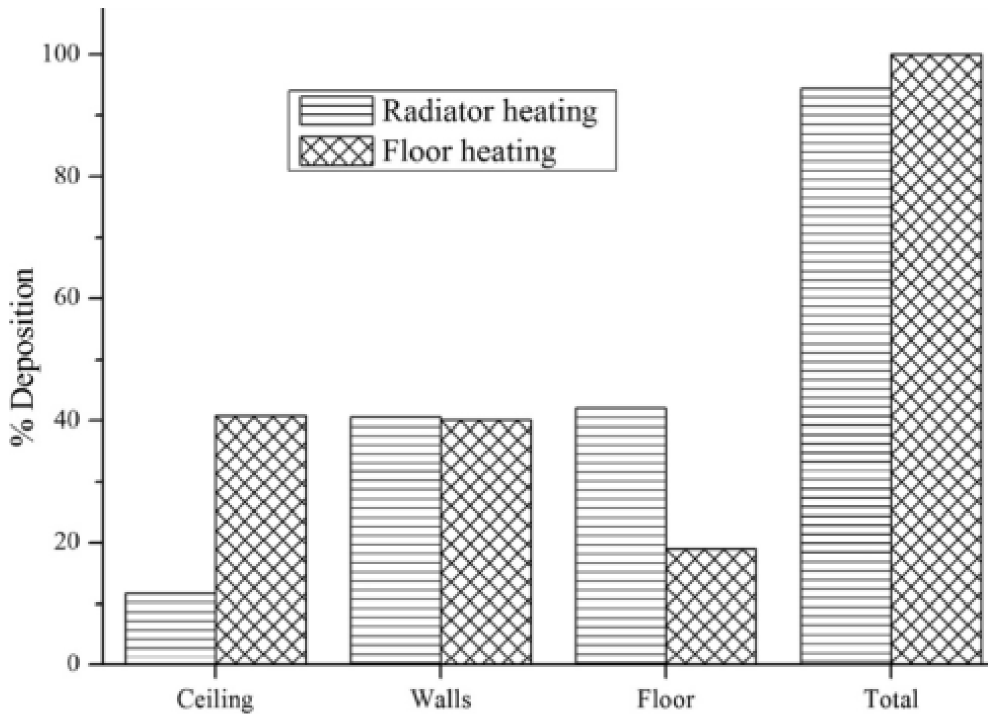


Figure 5. Comparison between radiator and floor heating systems for particle deposition on surfaces within the modelled room after 200 seconds (Golkarfard & Talebizadeh 2014).

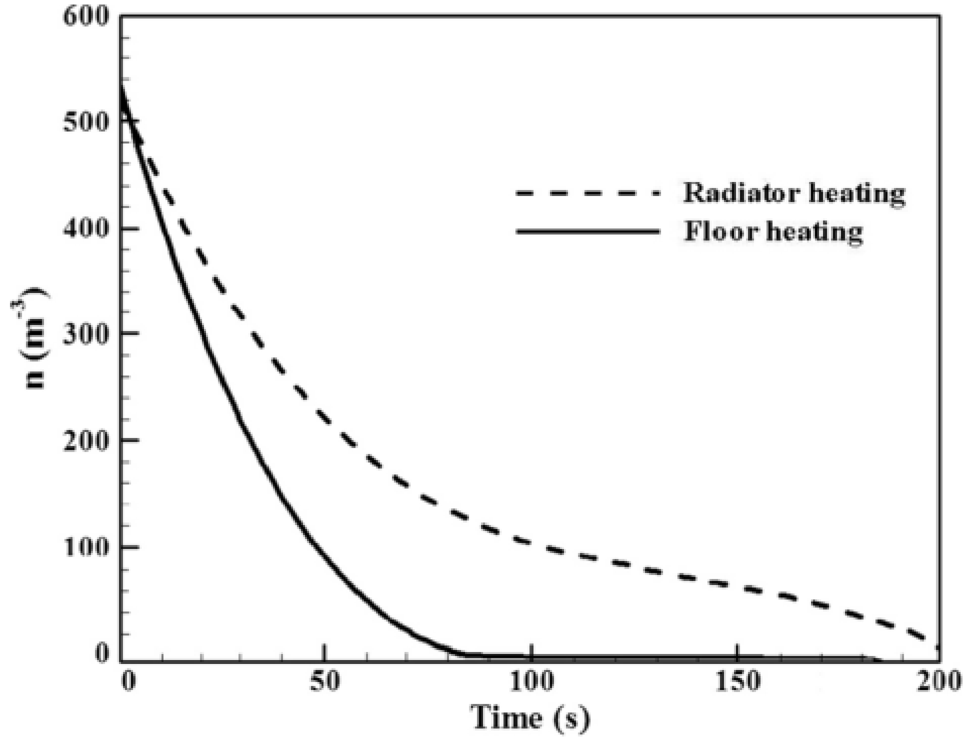


Figure 6. Comparison between radiator heating and floor heating systems for particle density (n) by cubic meter over 200 seconds (Golkarfard & Talebizadeh 2014).

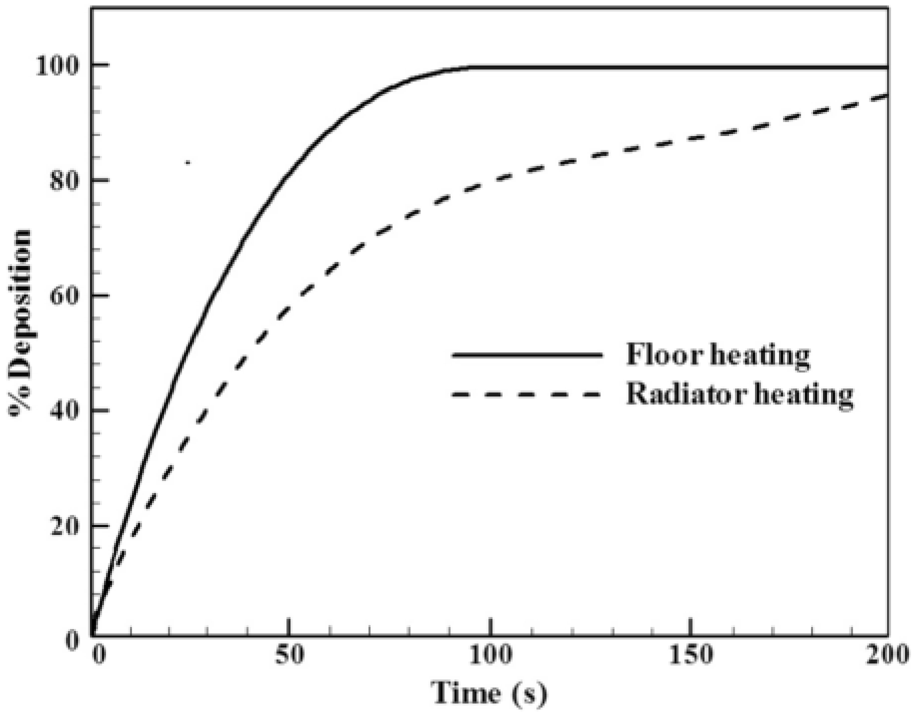


Figure 7. Comparison between radiator heating and floor heating systems for particle deposition percentage over 200 seconds (Golkarfard & Talebizadeh 2014).

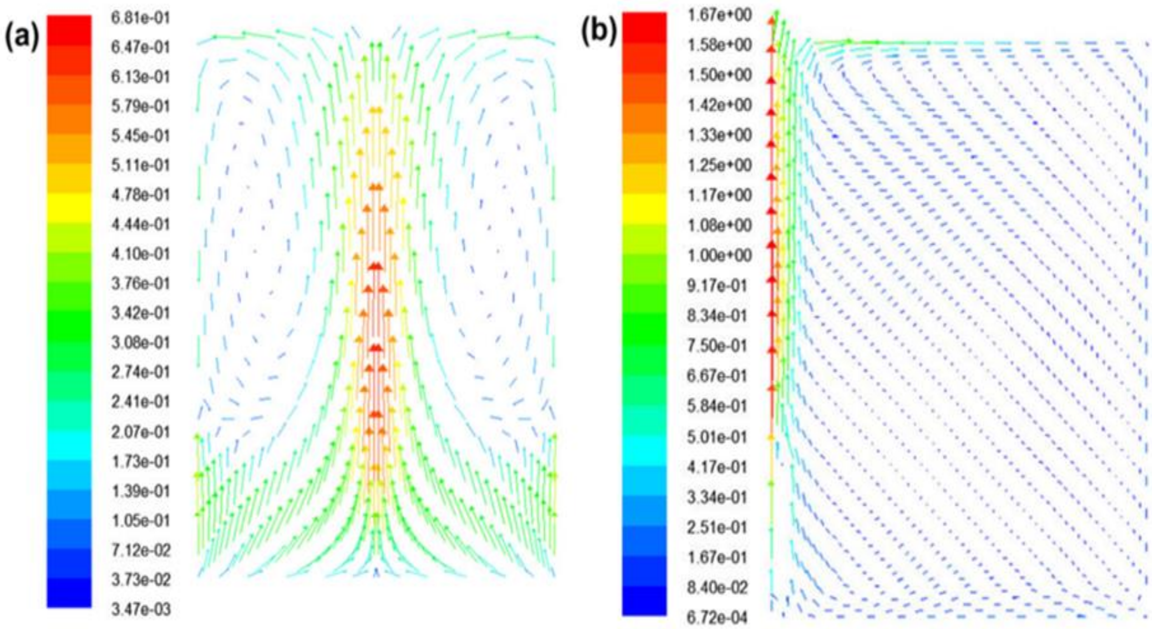


Figure 8. Velocity (m/s) vectors over the room midsection with (a) floor heating system and (b) radiator heating system (Golkarfard & Talebizadeh 2014).

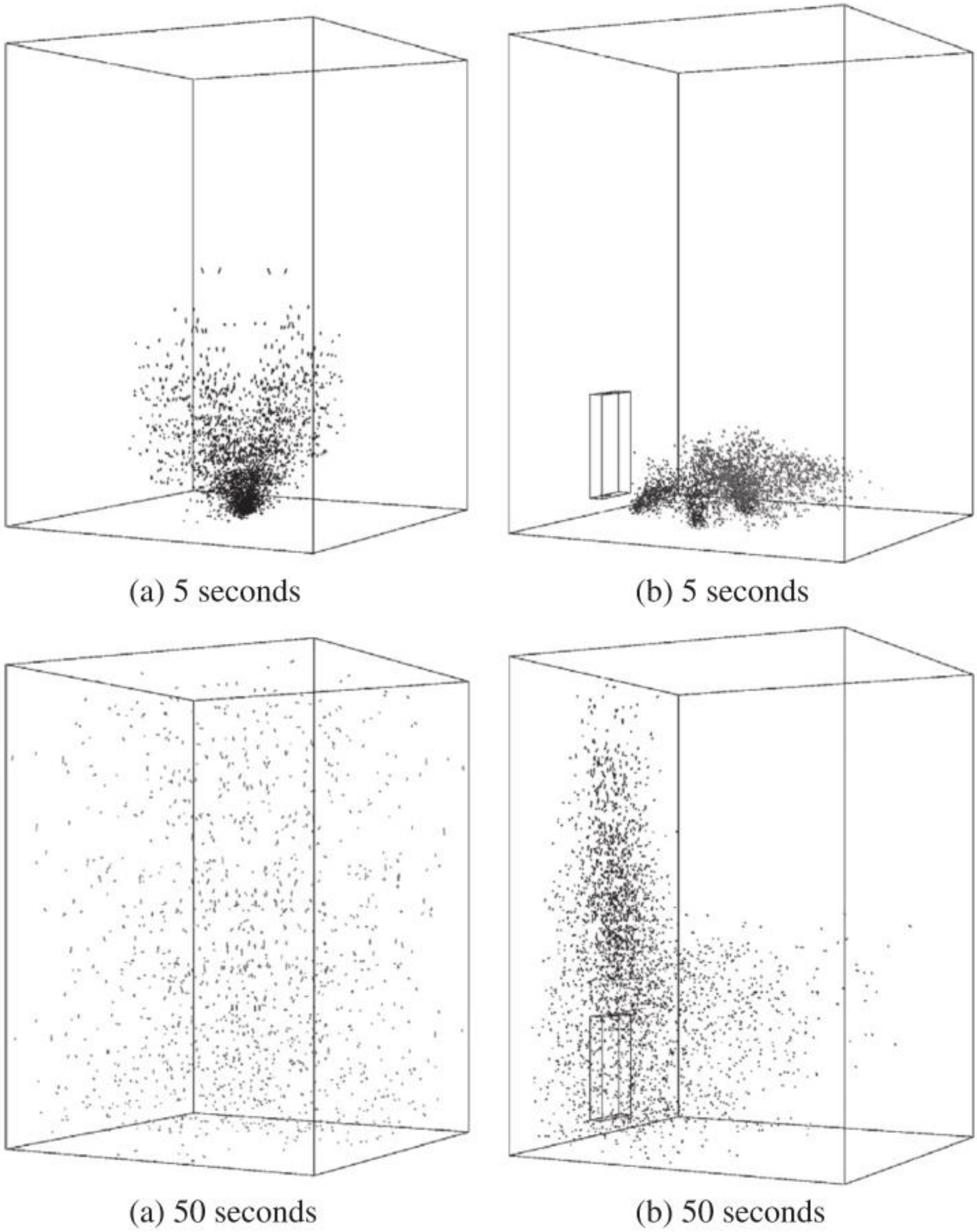


Figure 9. Particle position snapshots at 5 and 50 seconds for (a) floor heating system and (b) radiator heating system (Golkarfard & Talebizadeh 2014).

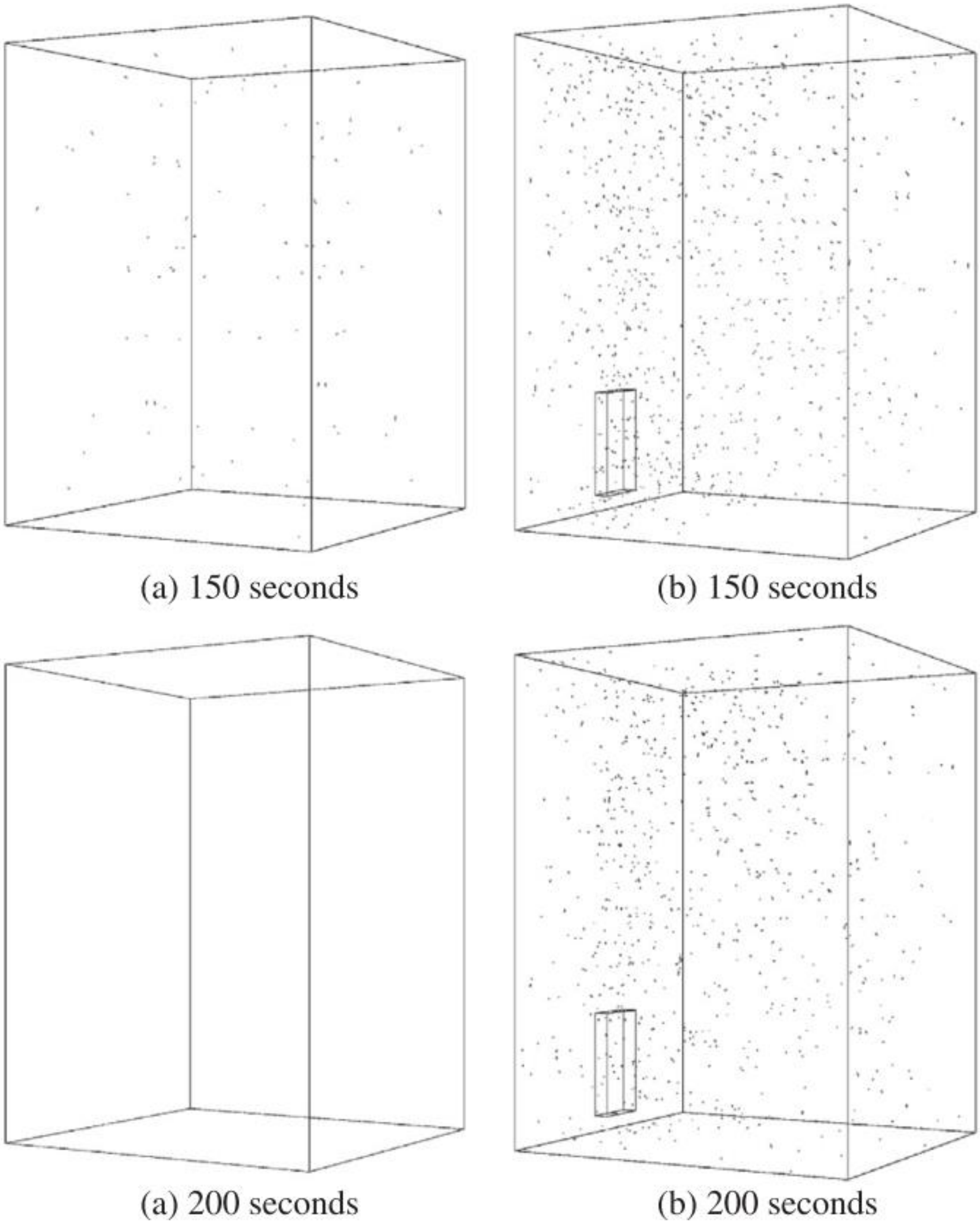


Figure 10. Particle position snapshots at 150 and 200 seconds for (a) floor heating system and (b) radiator heating system (Golkarfard & Talebizadeh 2014).

Other factors influencing air movement and dust deposition

Tham (2016) stated, in addition to supporting the findings so far, that heating and cooling processes as highlighted as well as ventilation and air distribution systems that mix the air, often with turbulence, generate flow paths that carry contaminants and facilitate exposure to occupants. Further to this, Tham (2016) also highlighted other influences on the movement and deposition of indoor air and particles including:

- Materials (wall finishes, furniture, and fabric) can emit or absorb particles depending on motivating environmental parameters such as temperature, surface air velocity and humidity.
- Equipment and processes in buildings may generate pollutants or move and re-suspend particles.
- Occupant movement and activities can generate pollution and re-suspend deposited particulate matter.

Air tightness in buildings

Between 1986 and 2006 house sizes became smaller in terms of floor area and volume. The reduction in volume when combined with air tightness and restricted air infiltration has resulted in internal air change rates reducing by close to 90% (Howieson 2014). Further to this Taylor *et al.* (2015) & Awbi (2017) highlights that increasing air tightness leads to poor air quality. In line with an attitude towards improving thermal efficiency and reducing energy consumption, homes have become less well ventilated (Knudsen *et al.* 2016). There are a number of studies looking at the issues of indoor air quality, heat comfort and ventilation (Gupta & Kapsali 2016; Knudsen et al. 2016), as these metrics in the home are connected with air changes required to improve indoor air quality, but can be at the expense of heat comfort in the winter. Ventilating homes is often an issue when concerned about energy consumption. Balancing air quality and energy for heating, particularly in winter months can be challenging for those wishing to save money and optimise their heating. Respondents to a research survey indicated that 70% aired the house for cleaning at least once every two weeks. However, those that did open their windows did so for less than 15 minutes, with only a few people allowing 30 minutes or more for an air change (Knudsen et al. 2016). Low ventilation may lead to high indoor humidity and moisture accumulation in building structures or materials. This may lead to increased dust mites, and particularly high humidity can increase the risk of microbial growth, and subsequently to microbial contamination and other emissions in buildings. In epidemiological studies, moisture damage in building was associated with a number of health effects including respiratory symptoms and diseases (Bornehang *et al.* 2001).

What this research highlights is that a lack of adequate air changes in buildings which are increasingly air tight could be contributing to indoor air quality issues, including those of dust accumulation in homes. With potentially up to 90% of time spent in indoor environments for some people (Alshitawi & Awbi 2011), combined with issues of air tightness and resultant increasing indoor air quality issues from lack of air changes, we are spending more time in environments which could be harmful to our health and will be discussed later.

Summary

From this research, it can be said that radiators influence the movement of air in a room. The velocity of the air and particles in the room is greatest above the radiator, where thermal plumes extend directly upwards and deflects across the ceiling. Air movement under the ceiling is complex where a large air circulation forms mixing hot and cold air. Air flow in the occupied zone of the room is towards the radiator, a downdraft forms on the wall opposite the radiator. Research modelling dust particle movement in a room compares floor heating system (FHS) to a radiator heating system (RHS). Both systems suspend dust in the air, however, RHS suspends the dust in the air longer and in higher quantities than FHS, despite RHS more likely to deposit dust on walls or floors. Small particles are more likely to suspend in the upper warm zone of the room, depositing on high level internal surfaces (e.g. tops of doors), while larger particles travel through the room space and deposit on the floor.

Occupants are at higher exposure risk to the particles in close proximity to the radiator. Sources of turbulent air (e.g. heating/cooling, ventilation, occupant movement) can re-suspend deposited particulate matter.

Air tightness for thermal efficiency in buildings could exacerbate dust accumulation due to lack of ventilation, particularly when human behaviour is taken into account with our decision to change the air in buildings and the length of time we typically spend indoors.

Stage 2: Understanding what is in dust and where those components have come from.

Dust collections in homes have taken place from analysing the contents of hoover bags, taking samples from floors or from tops of door frames. No studies have looked at the contents of dust from behind a radiator, so there is a possibility that the following contents may vary. Geographical region, climate, room occupants and other factors all influence the content of dust. Health consequences for this stage will be discussed in the stage 3 section. Not all contents in this section will necessarily have negative health consequences, particularly as microbial communities in the home can reduce prevalence of allergic disease development (Fujimura *et al.* 2010) and autoimmune disorders (Ege *et al.* 2011; Rook 2013).

The most common suspended matter is asbestos fibres, fibrous particulates (fibreglass or rockwool), bacteria and fungi, tobacco smoke, house dust mite (HDM) allergens, pollen and dust (Batterman & Burge 1995; Howieson 2014). Dust is a mixture of fibres, dead skin cells, bugs, soil particles, and residues of furniture, electronics and other domestic consumer products (Ouyang *et al.* 2017). On the other hand, outdoor dust contains (among other things) silica, combustion products, rubber, fungus spores, bacteria, and other whole and fragmented organisms (Batterman & Burge 1995).

Activities such as candle burning and those related to cooking were major air particle sources, with positive correlations found between soot concentration in dust and smoking, candles, cleaning and cooking activities, with smoking, candles and cleaning producing the strongest correlations (Isaxon *et al.* 2015). Home heating systems are not correlated with determining mean or baseline indoor ultrafine particle exposures. With exposure to ultrafine particles more closely correlated to cooking or smoking in the home. Although heating systems do not determine exposure, they do contribute to exposure (Weichenthal *et al.* 2007).

Peanut allergy is an important public health concern, particularly for infants. Where peanut consumption takes place, there are also traces of biologically active peanut protein in dust (Brough et al. 2013). Complimenting this, there have been other studies which have demonstrated quantifiable levels of protein from egg, milk and fish in vacuumed household dust (Witterman *et al.* 1995; Strid *et al.* 2004; Fox *et al.* 2009).

A number of compounds have also been found in household dust according to one study in Upsalla, Sweden (Ouyang *et al.* 2017). The contents include insecticides and fungicides, traces of antibiotics, flame retardants, plasticizers, industrial solvents and adhesive chemicals. See the list below:

- Phenylalanine - (Natural product)
- Metolcarb - (Insecticide)
- Streptidine - (Metabolite of streptomycin (an antibiotic))
- Azelaic acid - (Drug, plasticizer, lubricant)
- Sebacic acid - (Foam seating and bedding products)
- Triisobutyl phosphate (TiBP) - (Flame retardant)
- Tributyl phosphate (TBP) - (Flame retardant, plasticizer)
- Tris (2-butoxyethyl) phosphate (TBOEP) - (Flame retardant)

- Tris (1-chloro-2-propanyl) phosphate (TCPP) - (Flame retardant)
- Dibutyl phthalate (DBP) - (Plasticizer)
- Diisobutyl phthalate (DiBP) - (Industrial solvent)
- Dicyclohexyl phthalate (DCHP) - (adhesive chemical and coating additive)
- n-Butyl benzyl phthalate (BBzP) - (Plasticizer, adhesive and floor covering)
- Primicarb – Insecticide
- *N,N*-Diethyl-meta-toluamide (DEET) - (World's most widely used inspect reppelant and major active ingredient in anti-mosquito spray (Briassoulis *et al.* 2011))
- Benomyl - (Fungicide)

PBDE's are used as flame retardants and North American household occupant exposure to PBDE's has doubled every 4-6 years (Jones-Otazo *et al.* 2005). PBDE's are present in household dust, which is 20 times higher in North America compared to Europe (Jones-Otazo *et al.* 2005; Harrad *et al.* 2006). However, concentrations in the UK are higher than the rest of Europe (Harrad et al. 2006). Despite this PBDE's are banned in Europe for electronic devices under the Restriction of Hazardous Substances Directive 2002/95/EC (RoHS 1).

Finally, microbial taxa play a significant part of household dust. Composition of microbes found in homes are influenced by presence, identity and activities of occupants (Rintala et al. 2008; Täubel et al. 2009; Fujimura et al. 2010; Lax et al. 2014; Dannemiller et al. 2016). Pets are included in these occupants as the presence of pets and the resulting human exposure to the pets contribution to dust microbial communities (Fujimura et al. 2010; Dannemiller et al. 2016) can reduce the prevalence of allergic disease development (Fujimura et al. 2010). Indoor and outdoor dust samples harboured distinctive microbial communities, more so for bacteria than fungi. Bacteria and fungi inside homes are not identical to those found outdoors and attempts to link microbes to human health outcomes cannot rely exclusively on data collected from outside homes (Barberán et al. 2015). With sources of microbial taxa coming from a variety of sources, a detailed list through a study by Barberán *et al.* (2015) is provided below.

Bacteria associated with:

- Human skin
    - Staphylococcus
    - Streptococcus
    - Corynebacterium
    - Propionibacterium
- Vaginas
    - Lactobacillus,
    - Bifidobacterium
    - Lactococcus
- Faeces
    - Bacteroides
    - Faecalibacterium
    - Ruminococcus

Skin and faeces are more important sources of bacteria found in indoor dust compared to outdoor dust. Furthermore, these analyses show that bacteria from non-human occupants, including those taxa commonly associated with insects, including household insects (e.g. Wolbachia, Buchnera, Rickettsia and Bartonella) were found to be relatively more abundant inside homes (Barberán *et al.* 2015). Evidence of dogs or cats was predictable from bacterial phylotypes present in a sample (Barberán *et al.* 2015).

Fungi associated with:

- Moulds
    - Aspergillus
    - Penicillium
    - Alternaria
    - Fusarium
- Wood-degradation
    - Stereum
    - Trametes
    - Phlebia
    - Ganoderma
- Human skin
    - Candida
    - Trichosporon
- Gastronomically relevant
    - Saccharomyces
    - Pleurotus
    - Agaricus,

Some of the fungi and bacteria highlighted above found in house dust are a natural result of occupants' habitation.

Stage 3: Understanding the health implications from the exposure to household dust.

House dust mites

House dust mites thrive in high humidity environments which moistens their major food source: human skin scales. They excrete a range of highly allergenic proteins that have been identified both as a causal mechanism in the development of asthma, and as irritants likely to trigger and exacerbate asthmatic symptoms. The majority of dust reservoirs in dwellings contained house dust mite allergen levels above the WHO sensitisation threshold of 2 µg/g in fine dust, with 56% of beds found to contain concentrations known to cause an immediate acute reaction (10 µg/g) (Howieson 2014). Our dwellings are becoming warmer and more humid: conditions that are ideal for HDM infestation and proliferation. This is likely to be the key variable in driving asthma prevalence. It is estimated that the number of people with asthma will grow by more than 100 million by 2025. Similar to asbestos, a significant proportion of the current asthma pandemic and ill health that is being driven by poor indoor air quality is preventable if the Scottish and UK governments are willing to recognise the existing evidence base (Howieson 2014).

Microbial taxa

Majority of human time is spent indoors in increasingly urban environments, spending more time with microbial taxa (Klepeis *et al.* 2001). Microbial taxa in household dust can have both negative and positive impacts on human health. Negative impacts include triggers of allergies and asthma (Douwes *et al.* 2003; Salo *et al.* 2006), positive include reduction in incidence of allergies and autoimmune disorders (Ege *et al*. 2011; Rook 2013).

Persistence and severity of asthma has been associated with sensitization and exposure to *Alternaria Alternata*, one of the most common fungi associated with asthma. This fungi is normally associated with outdoor exposure, however, is also found in indoor environments. Spores are considered the primary source of fungal allergens; however, other biologically active molecules derived from fungi can be transported by house dust. There is a positive association between *Alternaria Alternata* in the home and Asthma (Salo *et al.* 2006). Mould exposure in homes has also been associated with Asthma and an otherwise net negative impact on health (Hamilton *et al.* 2015).

Proteins

As food proteins, particularly peanut protein, as well as milk, egg and fish have been found in dust samples, studies have been conducted to see what the impact is on human health. Peanut protein in house dust has been identified as a plausible route to peanut sensitisation in infants, and could be possibly contribute to the prevalence of peanut allergies in children (Brough *et al.* 2015); however, more research is needed. This is however further complemented with one study which found that the levels of egg and milk protein in house dust were high enough to elicit allergy response in patients with egg and milk allergies (Witterman 1995).

Particulate matter

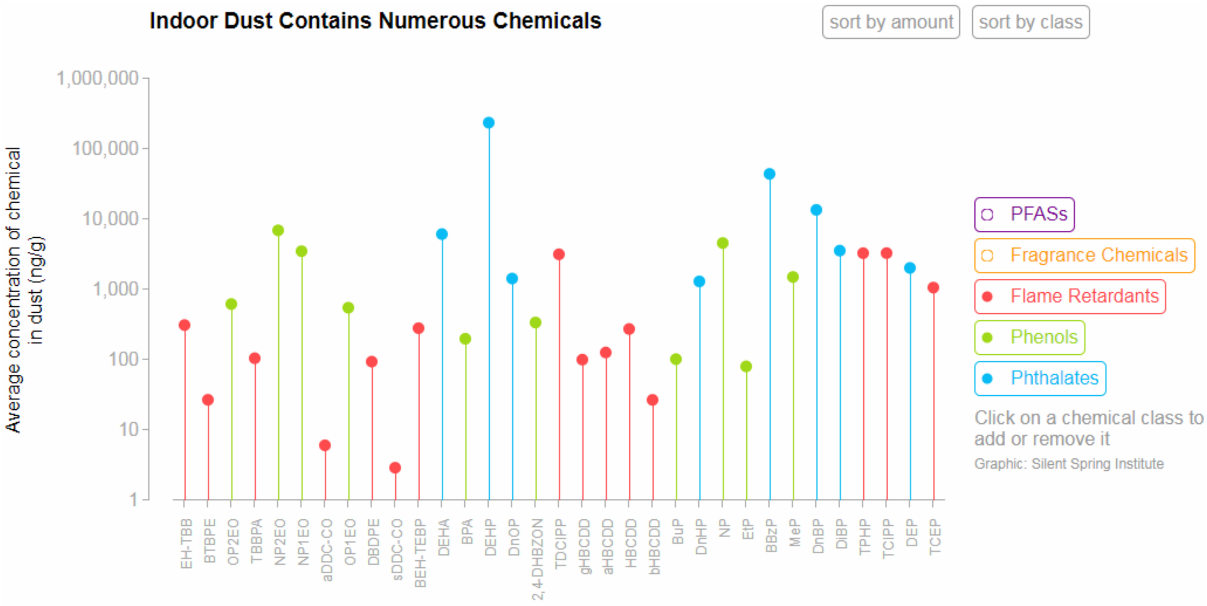
Particulate matter and indoor air quality is associated with cardiovascular disease (Uzoigwe *et al.* 2013; Samet *et al.* 2016). For particulate matter in indoor air, numerous studies indicate that these may affect occupant health even at very low values, making it very difficult to set a threshold concentration below which there are no effects on health (Vasile *et al.* 2016).

Chemicals

PBDE's have consequences for children's neurodevelopment, with negative consequences for reading skills and is associated with behavioural problems at age 8 (Zhang *et al.* 2017). Exposure to dust containing PBDE's has greatest impacts on toddlers (Jones-Otazo et al. 2005; Wang et al. 2014), and efforts should be taken to remove products from the home which contain PBDE's. Household cleaning of dust is a practical means to reduce one's exposure (Jones-Otazo et al. 2005).

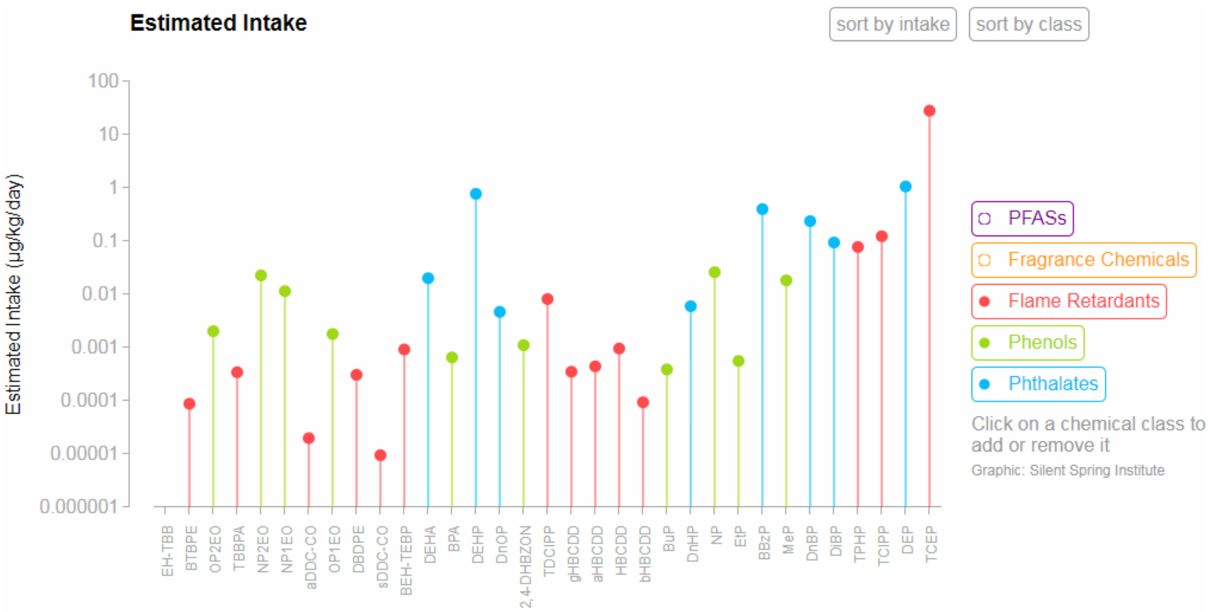
OPFRs (flame retardants) and phthalates are known environmental contaminants present in house dust (Meeker & Stapleton 2010). These are some of the more major concerns for contents in house dust was reviewed by Mitro *et al.* (2016) who looked at a review of inhalation, estimated intake, source of exposure, and health risks of flame retardants, Phenols, Phthalates, PFASs and Fragrance chemicals. Although exposure to these chemicals, particularly Phthalates (Kubwabo *et al.* 2016) can be highly variable (Mitro *et al.* 2016), there are registered health impacts. Phthalates are also endocrine disruptors which can inhibit testosterone synthesis (Howdeshell et al. 2008) and their levels in house dust have been associated with asthma and allergic symptoms in children (Bornehag et al. 2004). Flame retardants in household dust have been associated with alterations in hormone levels and decreased sperm counts (Meeker & Stapleton 2010). Mitro *et al.* (2016) has provided a visual representation of the dust content, estimated intake, exposure source and health impacts in Figure 11, Figure 12, Figure 13 and Figure 14 respectively. The Figures have been adapted to remove data on PFAS's because they are not inhaled and fragrance chemicals as they had no registered health impacts from dust in the data provided. Data is arranged by exposure to inhalation (right to left).

As can be seen in Figure 11 and Figure 12, concentration of a compound in household dust does not imply higher estimated intake, although it is a factor. Reducing concentrations in household dust will reduce estimated intake, however, estimated intake is also affected by the properties of the dust, and the source of exposure highlighted in Figure 13. Figure 13 demonstrates that all the components listed in household dust has a route to exposure via inhalation, however, those with inhalation exposure as the highest source are broadly more correlated to estimated intake, as can be seen in Figure 12. Figure 14 highlights the health impact hazards from exposure, but data related to thresholds and severity of the health impacts is not provided by Mitro *et al.* (2016) except to say that further research, particularly with cumulative exposures and impacts is required, particularly as co-exposure of multiple chemicals is likely. Mitro *et al.* (2016) concludes by stating that the indoor environment is a haven for chemicals associated with reproductive and developmental toxicity, endocrine disruption, cancer and other health effects.



Average (geometric mean) dust levels in nanograms of chemical per gram of dust for the 45 chemicals reported in at least three data sets. The average concentration of DEHP is about 45,000 times higher than PFBS.

Figure 11. Average concentration of chemicals in dust measured in ng/g for Flame Retardants, Phenols and Phthalates (Mitro *et al.* 2016).



This graph shows the estimated daily residential intake of each chemical for a 3-6 year old child (µg/kg/day), based on the pooled GM concentrations of each chemical in dust from the meta-analysis.

Figure 12. Estimated human intake of chemicals in household dust, measured in µg/kg/day via three pathways (ingestion, inhalation and dermal exposure from air) for Flame Retardants, Phenols and Phthalates (Mitro *et al.* 2016).

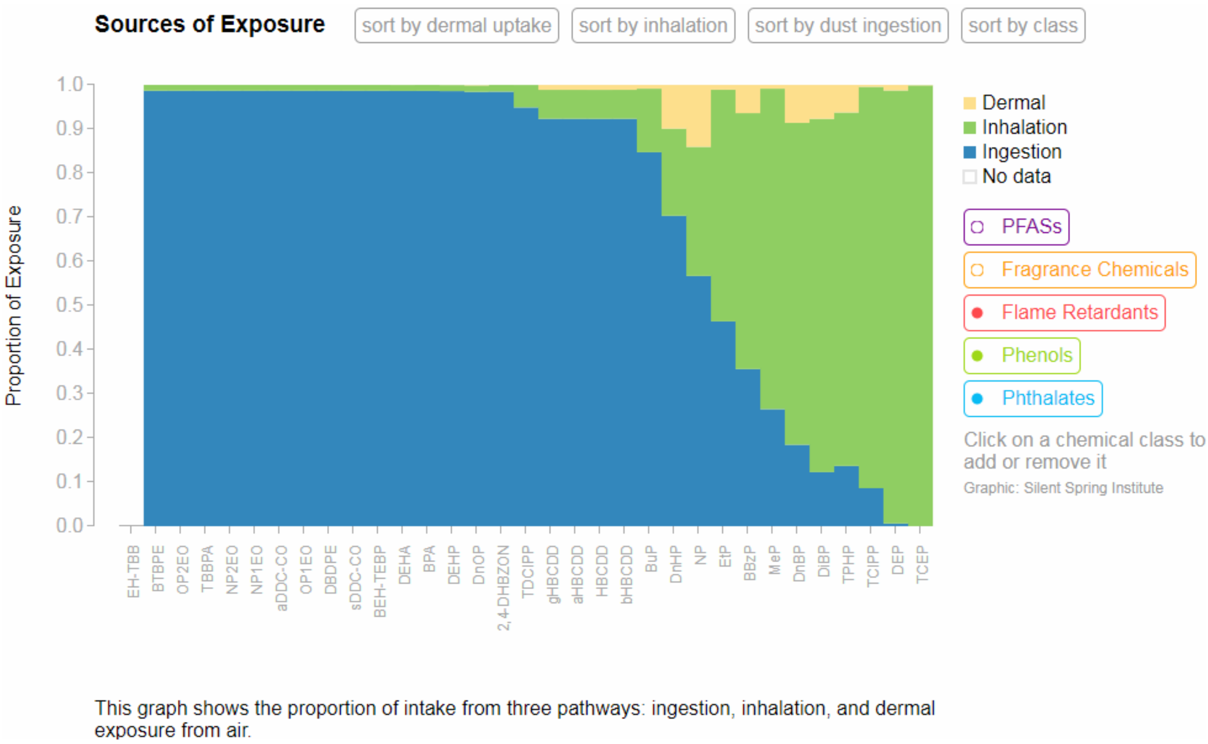


Figure 13. Sources and proportion of exposure to household dust chemicals including Flame Retardants, Phenols and Phthalates. Sources of exposure include Dermal, Inhalation and Ingestion (Mitro *et al.* 2016).

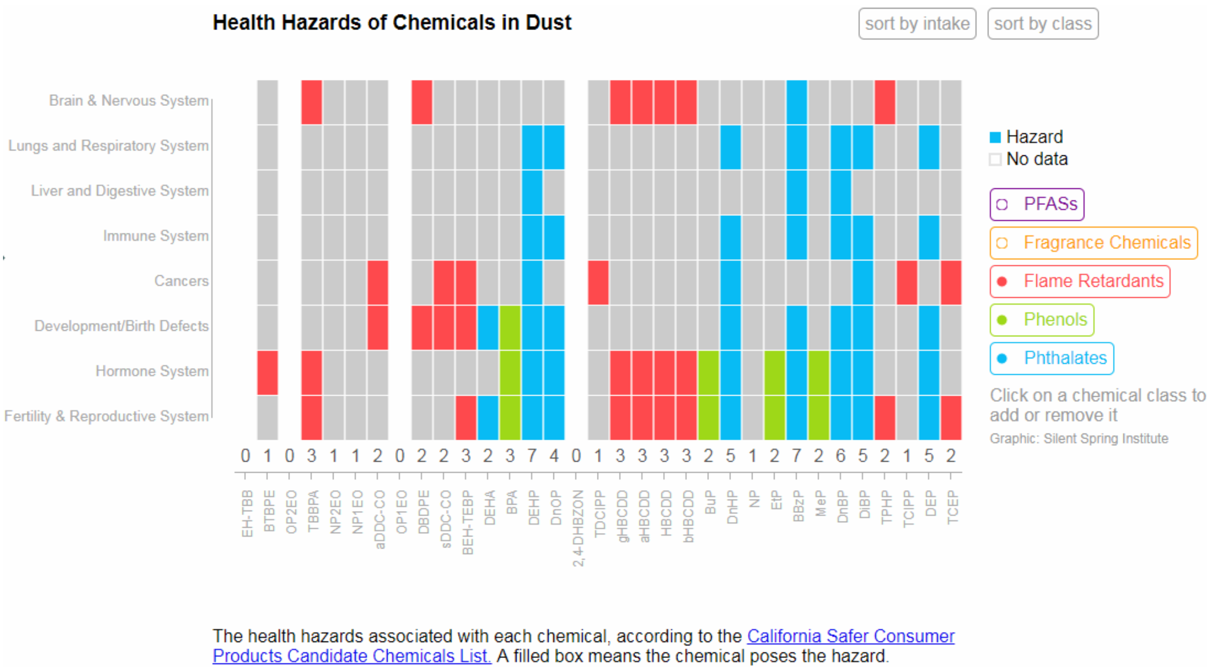


Figure 14. Listed health hazards from Flame Retardants, Phenols and Phthalates in household dust (Mitro *et al.* 2016).

Stage 4: Investigating what the hospital admissions figures for highlighted health conditions and what connections can be made to dust implications.

Asthma and Allergy

In order to understand the burden of asthma, it is important to investigate not only emergency hospital admissions due to the illness, but also the financial burden of the illness. The total UK emergency hospital admissions due to asthma were 65,500 in 2013, 73,000 in 2014 and 71,000 in 2015. From this data 24.64% of patients were between the ages of 40 and 49, surpassing the 13.81% of patients admitted over the age of 65, who are considered to be a more vulnerable age group. The percentage of patients admitted to hospital in emergencies related to asthma in the same time period, under the age of 5 and between the ages of 5 and 10, were 14.29% and 13.90% respectively. This means that children under the age of 10 were the highest admitted age group, with a total of 28.20% (Asthma UK 2017). As seen in Figure 15 and 16, months with the lowest admission rates were in August, followed by a significant increase in September and the following winter months (Asthma UK 2017). Figure 16 shows a particular spike in emergency admissions in the winter period of 2014. Winter 2014/2015 was an average winter according to historical trends (Met Office, 2016) and so the reason for peak in admissions is therefore unclear. Asthma can be triggered by cold weather, yet cold weather is not the sole factor for the winter 2014/2015 admissions peak, indoor air quality could also be a factor in causing this peak (Howieson 2014). Further research would be needed to rule out other potential triggers that could be attributed to this spike.

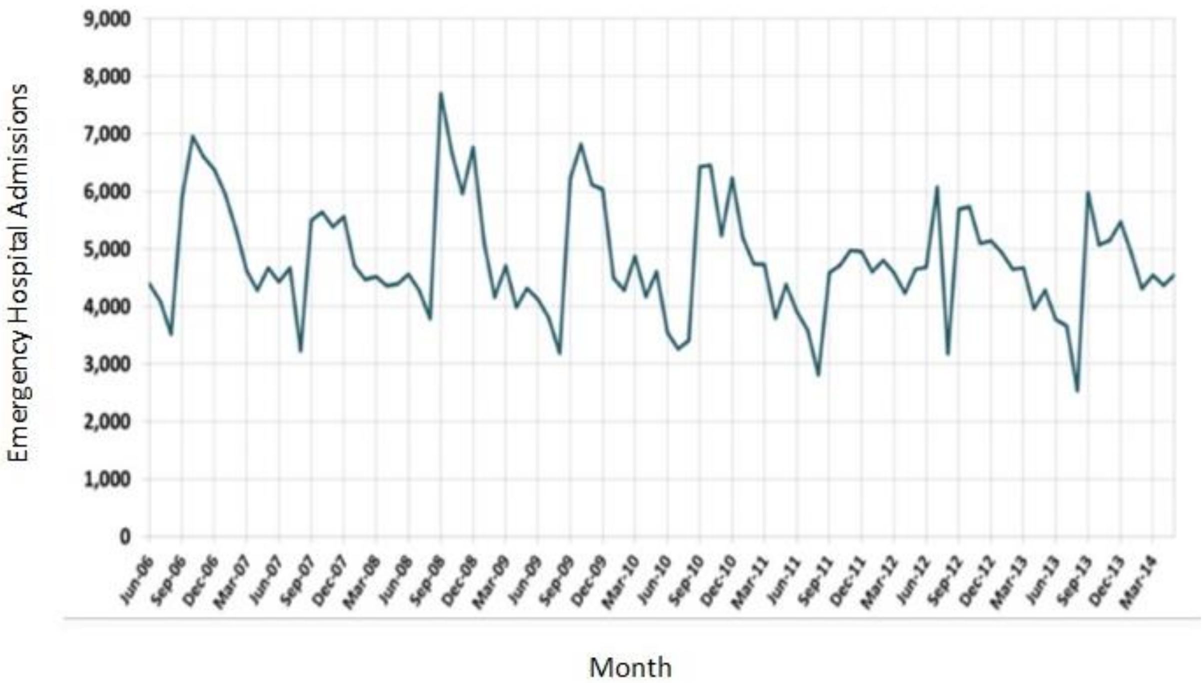


Figure 15. Emergency Hospital Admissions from 2006 to 2014 (NHS Digital, 2014)

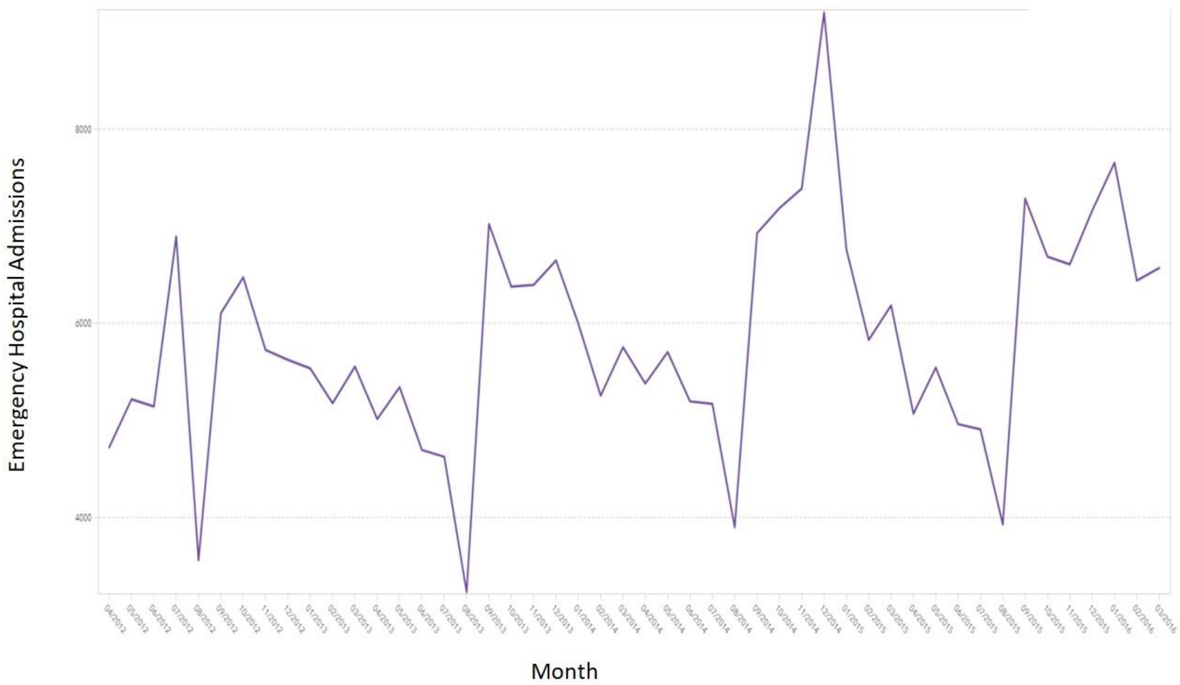


Figure 16. Asthma hospital admissions by month between April 2012 and March 2016 (Asthma UK 2017).

A cross sectional study of 2010/2011 data from GP practices in England found that in total 3,134,106 people were recorded as having asthma, of these 55,570 people were admitted to hospital in the case of an emergency (Fleetcroft, et al., 2016). This value is close to the average annual emergency admission rates observed from the Asthma UK data portal. The British Lung Foundation analysed statistical data found within the Respiratory Health of the Nation project. In relation to hospital admissions it was found that between the 2008 and 2012 approximately 60,000 patients per year were admitted to hospital and required 200,000 days of hospital bed usage (British Lung Foundation, 2016). When this figure is broken down it equates to 164 people being admitted to hospital each day.

Asthma UK has created an online tool which takes all current asthma data and transforms it into visual data such as graphs and charts as well as providing the raw data used. After investigating the raw data emergency admissions rates could be calculated, these can be seen in Figure 17.

	2013	2014
January	5533	5980
February	5174	5256
March	5551	5800
April	5011	5411
May	5344	5719
June	4708	5201
July	4639	5165
August	3237	3906
September	7036	6928
October	6377	7185
November	6393	7361
December	6632	9134
Total	65635	73046

Figure 17. Table showing emergency hospital admissions from 2013 to 2014 (Data taken from Asthma UK, 2017)

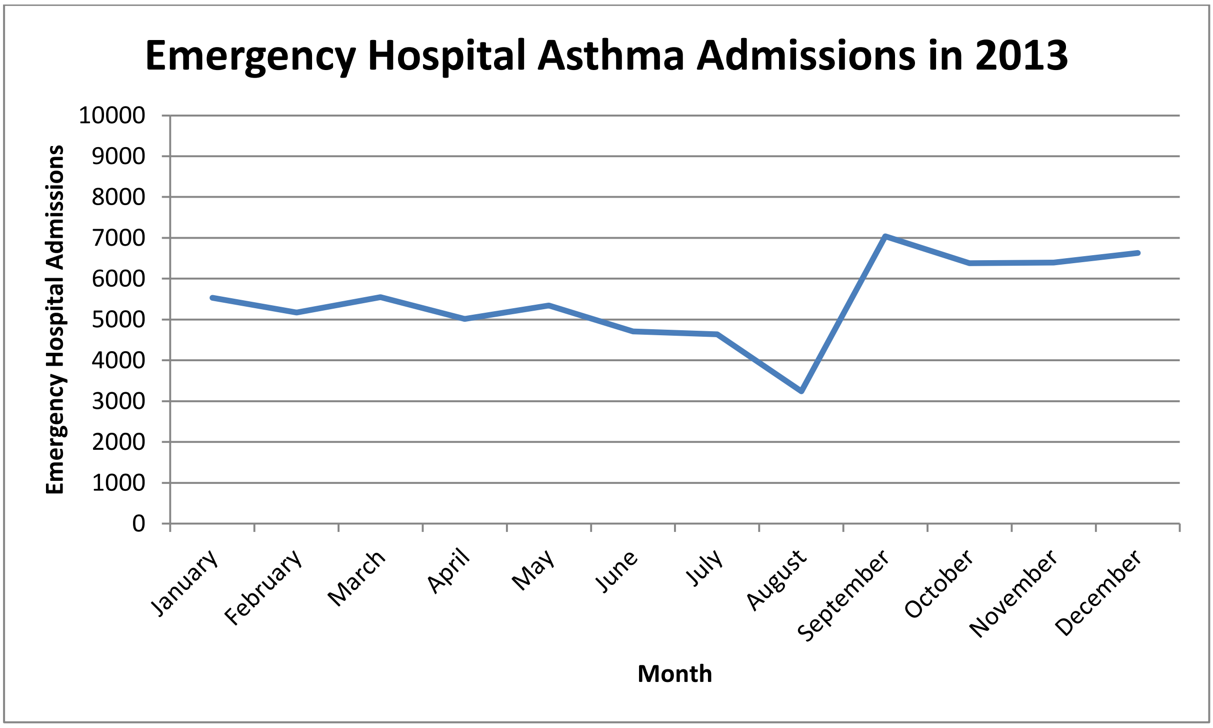


Figure 18. Graph showing the emergency hospital admissions for asthma in 2013 (Data taken from Asthma UK, 2017)

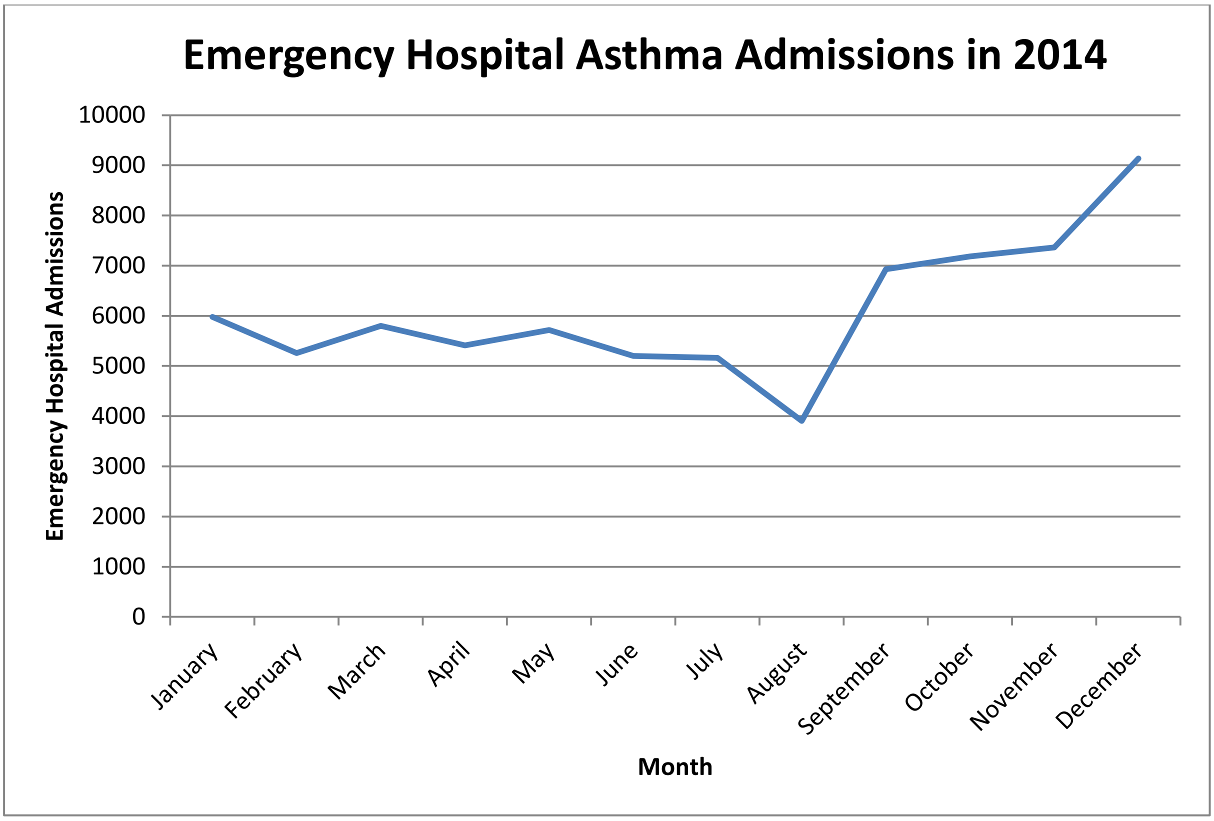


Figure 19. Graph showing the emergency hospital admissions for asthma in 2014 (Data taken from Asthma UK, 2017)

The data collected has been processed into graph form in order to give a visual representation of the emergency admission data. The above graphs (Figure 18 and 19) show the general trends for the data collected by Asthma UK. The main observation which was found was that the emergency admission rates drop significantly in August and then increase dramatically in September as previously mentioned, but it was also observed that in general a higher average of admissions occur between October and December.

This sharp fluctuation in admissions currently has no definitive explanation. It has been suggested that there is a seasonal pattern to be observed yet one of the most common assumptions is that the observed peak in September is associated with children returning to school from the summer break. Interestingly this observation is not exclusive to the UK, it has also been observed in Canada, the USA, Mexico and Israel. A crucial piece of evidence for this theory is that in the southern hemisphere this peak is observed in February which coincides with regional summer holiday timings (Larsen, et al., 2016). The admission of children accounts for the largest proportion of emergency admission with around "two in five were under 15" (NHS Digital, 2014). It therefore is logical to assume that if returning to school did expose children to more risk factors, then the increase in hospital admissions would be large enough to influence the monthly admission results due to children accounting for approximately 40% of the entire sample.

Another hypothesis is that this increase in admissions during September may be due to colder weather being present after the summer months, in turn causing radiators to be used for the first time after a period of inactivity. When the radiator is not in use dust accumulates and will be dispersed into the atmosphere upon use, as explained in the NHS Estates: Infection control in the built environment guidelines (NHS Estates, 2002).

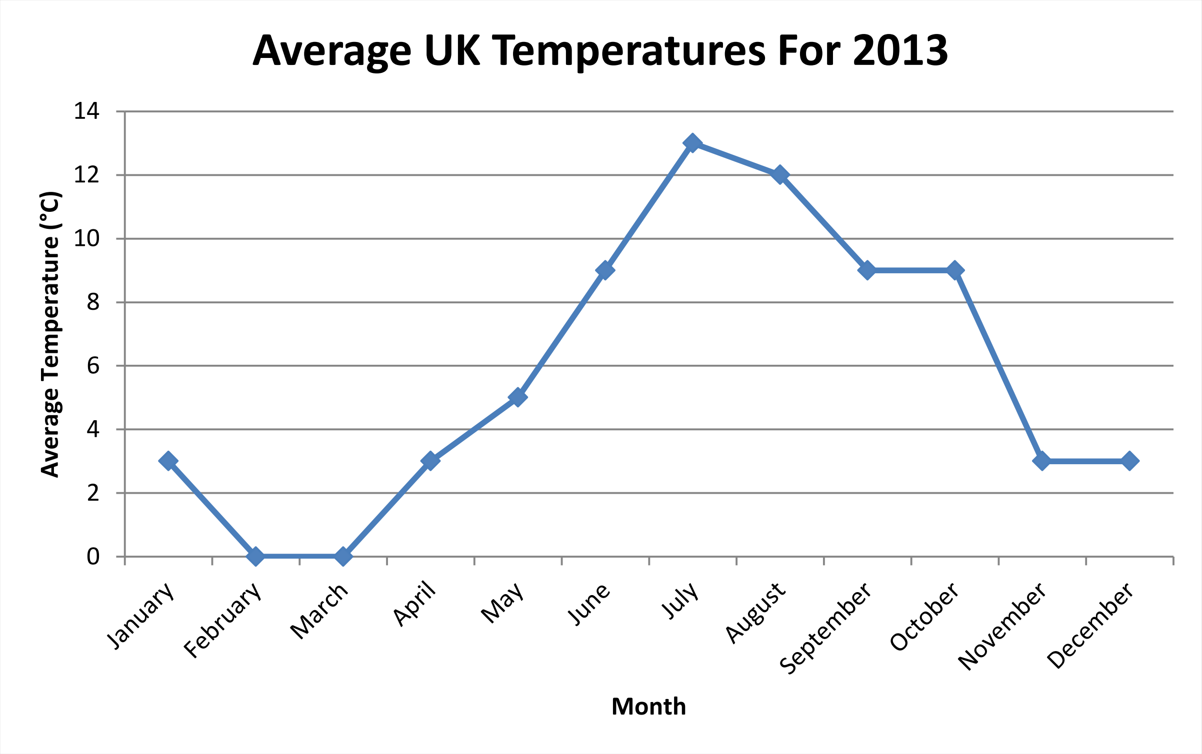


Figure 20. Graph showing average monthly UK temperatures in 2013 (Met Office, 2017)

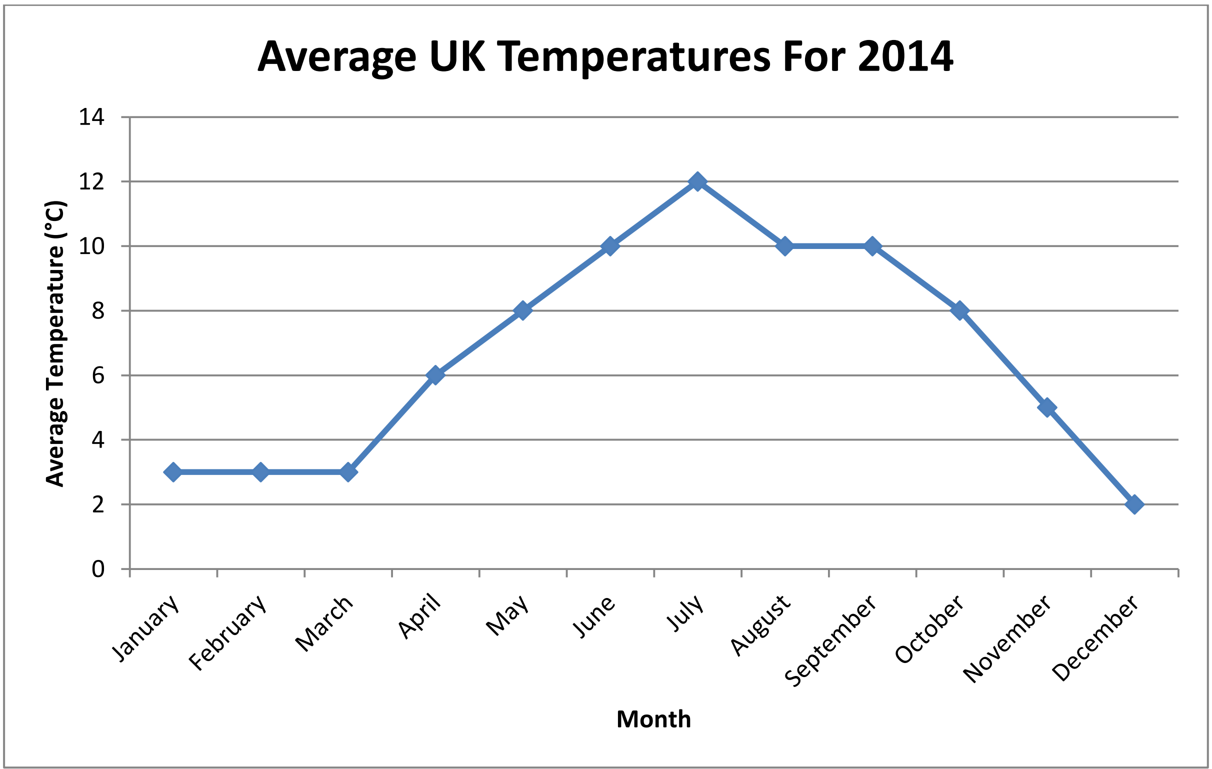


Figure 21. Graph showing average monthly UK temperatures in 2014 (Met Office, 2017)

Figures 20 and 21 show the average temperatures in the UK for the 2013 and 2014 period. This demonstrates that September onwards is generally when temperatures begin to decrease for the winter season.

In summary the reason this pattern occurs has not been scientifically proven. There could be other factors that are currently unknown which may influence these reactions such as different allergens being found at that specific time of year (i.e. proteins such as milk, fish, egg peanut), pet dander etc. Similarly, an illness developing over a long time frame such as cardiovascular disease will not be adequately displayed within the emergency admissions data and therefore this data will not be representative of such cases.

Death Rates

In the UK alone between 1000 and 1200 deaths have occurred annually since the year 2000 (NHS Yorkshire and the Humber, n.d.). This equates to approximately 3 deaths per day (statistically between 2.74 and 3.29 deaths daily). An article published in the Journal of Community Nursing states that "every 10 seconds someone in the UK has a potentially fatal asthma attack" it also supports that the death toll for asthma within the UK is 3 people per day (Munde, 2017).

On a worldwide scale death rates related to asthma much higher. The World Health Organization (WHO) states that the largest risk factors for asthma are "inhaled substances and particles", it is estimated that in 2015 alone 383,000 people died due to asthma worldwide (World Health Organization, 2017).

The British Lung Foundation states that whilst death rates for asthma are relatively low when compared to other diseases such as lung cancer, the death rates are still too high because asthma can be easily managed. This is supported by The Royal College of Physicians, as it is predicted that if the disease was monitored and managed more efficiently it could dramatically reduce mortality (British Lung Foundation, 2016). More importantly it is predicted that "90% of deaths are associated with preventable factors" (NHS Yorkshire and the Humber, n.d.).

Cost of Treatment for Asthma

When calculating asthma costs and its impact on a larger scale it is important to consider both the direct and indirect costs. In the UK approximately 5.4 million people are currently diagnosed and being treated for asthma (NHS.uk, 2014). When investigating the UK asthma costs approximately £1.1 billion per annum in treatment costs. When examining data from 2011-2012 this can be broken down as £660 million on medication related to asthma, £154 million for hospital consultations, £143 million in disability claims and £123.2 million in hospital care (Mukherjee, et al., 2016)

Patient specific costing data for the UK couldn't be found yet countries which have a similar climate and population size did have patient specific costing data. The Netherlands has been shown to have a similar climate to the UK (Hatch, 2014). Data suggests that in the Netherlands in 2007 asthma cost approximately €287 Million which equates to €530 per patient, 70% of this cost was attributed to pharmaceuticals. Sick leave was also investigated which cost €1200 per person on average (Suijkerbuijk, et al., 2013). It was also calculated that asthma patients are expected to increase from 443,000 in 2007 to 567,000 in 2032, this is an increase of approximately 28%. Healthcare costs of asthma in the Netherlands are also expected to increase with estimates suggesting costs are expected to increase by 100% by 2032 (Suijkerbuijk, et al., 2013).

The Netherlands may have a similar climate to the UK but it has a far smaller population, a more representative comparison could be France. In 2017 France had a population of approximately 67.14 million, whilst the UK had a population of approximately 66.01 million (The World Bank, 2018). A study from 2004 summarises the costs of asthma within France as costing €1.5 Billion annually. It also goes further to break down these costs into stable patients, patients who have a minimum of one acute attack and patients who are hospitalised these costs equate to €289, €1052 and €3811 respectively (Chouaid, et al., 2004). These costs may not be representative of patient costs within the UK, yet due to population size and climate being equivalent the costs could potentially be comparable between the countries.

When investigating a larger country such as the USA, costs are considerably higher. On an annual basis the indirect and direct costs of asthma cost an average of $4912 per person being treated with asthma, with around 65% being associated with direct costs and 35% being associated with indirect costs. Direct costs can be attributed to pharmaceuticals, hospital visits, and non-emergency ambulatory visits, whilst indirect costs were attributed to the termination of work and loss of work days (Cisternas, et al., 2003). As a whole the cost of asthma to the United States amounts to $56 billion, approximately half of this can be directly associated with severe asthma patients (Hankin, et al., 2013). Interestingly, the severity of the asthma the patient suffers is related directly to how much the treatment will cost. Mild asthma cost $2646, moderate asthma cost $4530 and severe asthma cost $12,813 (Cisternas, et al., 2003).

Stage 5: Case studies of radiator deep cleaning in hospitals

When investigating the prevalence of disease within hospitals, this section of the report will focus on cleaning within hospitals and what lengths current healthcare services such as the NHS go to in order to ensure a clean environment.

Cleanliness in relation to the healthcare sector (both premises and equipment) has been classed as a key issue for the NHS since 2000 (National Patient Safety Agency, 2010). It is important to consider current hospital cleaning regimes. Some studies have noted that the radiator may be a potential area of concern when considering cleanliness. A study by Dancer noted that dirty hospitals can be considered to be linked with the outbreak of “superbugs”; to combat this hospitals should have a specific cleaning regime. The study suggests that the radiator may be considered a “general surface” which is cleaned in the same way as floors, beds, lockers and clinical equipment (Dancer, 2009). Similarly, in a more recent study carried out by Dancer it is outlined that within a hospital every surface can be defined in one of two ways; critical or non-critical. Radiators fall under the non-critical category along with floors, furniture, doors, wall fixtures and “grilles and other ventilation components” (Dancer, 2014). Of these components the radiator is one of the only surfaces which has a completely inaccessible area which cannot be easily cleaned with traditional methods. Studies have also highlighted potential links with outbreaks of certain infections and radiator cleanliness. One study investigated the outbreak of C Difficile which was linked to a dirty radiator cover which could not be cleaned. It was noted that the outbreak happened in November shortly after the radiator had been used for the first time after a period of not being used, and that potentially other factors may have contributed to the outbreaks (Teare, et al., 1998). This poses the question of whether the back of a radiator which cannot be cleaned may also contribute to the outbreak of hospital infections.

Testing within both a hospital ward and operating theatre was carried out by Griffith et al. This involved testing 113 surfaces over 14 days using methods such as visual assessment, microbiology testing and ATP bioluminescence testing (Griffith, et al., 2000). For the hospital ward this testing found that when using the microbiology testing and ATP bioluminescence testing the results showed a failure rate of 70% and 76% for the surfaces, similarly for the operating theatre the failure rate of the ATP bioluminescence testing was 61%. However it is important to note that these studies did not include the use of biocide, when further testing was carried out with a hypochlorite based sanitiser the results that were observed were ”much lower”.

The NHS’s National Patient Safety Agency has released a document which outlines the specifications in regards to cleanliness in the NHS. This document describes radiators as a “key element” and states that in order to meet the standard of cleanliness required “all parts of the radiator (including between panels) should be visibly clean” the radiator should also show no signs of “blood or body substances, dust, dirt, debris, adhesive tape or spillages” (National Patient Safety Agency, 2010).

In very high risk areas (operating theatres, intensive care units etc.); high risk areas (toilets, general wards etc.) and significant risk areas (laboratories, pathology departments etc.) radiators require one full clean daily (NHS 2007). In low risk areas (administrative areas, non-sterile supply areas etc.) they require one full clean on a monthly basis. In a 2011 Scottish health report, 3 wards were below standard due to dust on radiators (HEI 2011). A Central London hospital achieved 97% in terms of cleanliness, however, even in a hospital that scores so highly, dust behind radiators in bathrooms was still common (Healthcare Commission 2005).

Within the NHS's cleaning procedure manual numerous methods of removing dust have been outlined as well as deep cleaning areas which include dust. The types of cleaning include; damp dusting, suction cleaning and Kez mopping. Damp dusting consists of using damp paper to prevent dust escaping into the air when it is moved, whereas suction cleaning is using vacuum suction to remove the dust and Kez mopping uses dry paper towels attached to a mop. Radiators have areas which can be hard to clean so steam cleaning is also used to "remove dirt from these inaccessible areas" (NHS: Royal United Hospital Bath, 2009).

This report also outlines the deep cleaning process and notes that deep cleaning is pre-planned for the year and is carried out by a specific team of cleaners. Once an area has been deep cleaned it must then be signed off by either a cleaning supervisor or a team leader, this is to ensure that the clean has been carried out to an appropriate standard. Within each area a set of procedures are followed in a specific order. In regards to radiators the document states that the cleaner must "remove radiator covers, radiators to be initially suction cleaned followed by steam cleaning then allow to air dry and replace covers" (NHS: Royal United Hospital Bath, 2009).

Frequency of cleaning is quoted as being one full clean per day in high risk areas such as a consulting room, treatment room and anywhere that minor surgery may take place. In lower risk areas such as storage rooms and meeting rooms one full clean must be carried out on a monthly basis (Leeds Community Healthcare NHS Trust, 2014).

The NHS's Infection Control in the Built Environment guidelines has a section dedicated to heating and temperature control guidelines. Within this, heat emitters such as radiators are also covered. It is observed that heat emitters that have a cover had the largest concern in relation to infection control. This is due to dust build up on the underside and within the inside of any dust covers. This dust "has been found to contain MRSA and other potentially pathogenic organisms". This effect has been attributed to radiators being throughout winter and dispersing bacteria covered dust particles into the atmosphere (NHS Estates, 2002).

Summary

From this research it can be seen that within healthcare organisations such as the NHS, cleaning is a key issue which has many guidelines and regulations which need to be followed in order to ensure an appropriate level of patient risk is mitigated. Radiators themselves are areas which are recognised as having the potential of harbouring deadly pathogens which can endanger patients. To eliminate this specific outlines and cleaning procedures such as steam cleaning have been utilised. Research has not only investigated dust trapped inside radiator covers but also beneath radiators, currently little research has investigated dust trapped in between the back of the radiator and the wall on which it sits. This area has the potential to be a refuge for dust particles, presumably comprised of the same dust particles which carry harmful pathogens.

Other areas of interest

Other Factors – SIDS

Sudden Infant Death Syndrome (SIDS) is when a child below the age of 1 year old suddenly dies with no clear explanation, currently it is considered to be one of the leading causes of mortality in infants (Athanasakis, et al., 2011). Whilst studies have not generated a clear and defined link between SIDS and indoor air quality, many researchers have suggested that there should be further research conducted to find if there is a link between these two factors. One article carried out a literature review and found six studies which had reported statistically significant links between air pollution and SIDs, yet three further studies found no link. The literature review suggested that future research should have a particular focus on indoor air quality, and ultrafine particles (Tong & Colditz, 2004). Dust as a vehicle for the spread of disease resulting in SIDS has also been investigated. This study found that clostridium botulinum isolates taken from a child's intestine that had died of SIDS, was "genetically similar" to clostridium botulinum isolates taken from dust in the surrounding area. This shows that dust may be associated with SIDS, as it is a carrier of pathogens which can be inhaled by infants (Nevas, et al., 2005).

Other Factors – Dust Mites

Another factor that contributes to asthma is dust mites. The NHS's Hillingdon Hospitals outline that dust mites produce an allergic reaction in some people due to allergens being present in their droppings; these droppings become airborne and are inhaled by people nearby. The report describes that order to reduce dust mites, one of the most important factors is to prevent the build-up of dust. This is achieved by regularly cleaning areas where dust can build up (The Hillingdon Hospitals NHS Foundation Trust, 2011).

One study has suggested there may be a link between "seasonal changes" and levels of dust mite allergen exposure. The study concluded that there may be an increased level of airway responsiveness during the autumn period (Van Der Heide, et al., 1997).

Another study has investigated the relationship between the allergens of dust mites and asthma. It acknowledged that concentrations of dust mite allergens within the air are not only influenced by dust that has settled but also by "ventilation and/or domestic disturbance" (World Health Organization: International Workshop Report, 1988). The conclusions of this study also stated that one main cause of reactions in allergic asthma sufferers is when being exposed to dust mite allergens.

Other Factors – Pet Dander

Another risk factor aside from household dust is pet dander. Pet dander is dried skin flakes from an animal which are small and become airborne, these can be inhaled and in turn trigger asthma. This kind of asthma is called "allergic asthma". However, people can be an asthma sufferer but have no adverse effect to pet dander unless they are themselves allergic (Asthma UK, 2016). Radiators can potentially circulate air which contains pet dander, continually exposing occupants to allergens. The use of radiant heating (directly through the walls or floor) has been shown to potentially be more beneficial for people with these allergens because "radiant heating is dust free because there is no circulating air to carry dust particles, pet dander, or other particles (Davis, 2008). It has been estimated that in the USA, allergic asthma sufferers which react to pet dander yet continue to live with pets could increase the cost of treating asthma by $0.5-$1 billion per annum. This figure could be considerably higher due to work days lost not being considered (Ownby & Johnson, 2016).

Other Areas of Consideration

With patients over 65 being considered a more at risk age group, an area which could be considered as needing to be cleaned more regularly are care homes. With care homes being densely populated with elderly residents the effects of dust particles may have a greater effect than with other age groups. The NHS has guidelines for cleanliness within care homes which is similar to guidelines within the hospital and dental settings. It outlines that radiators need to be cleaned once a day in both moderate and high risk areas, radiator covers also need to be removed and cleaned as well as general areas such as floors and electrical items being cleaned daily (NHS: National Patient Safety Agency, 2010). Similarly, infants are considered to be a high risk age group and therefore children's nurseries and day care centres may also need to clean their radiators more frequently.

Conclusions and moving forward

In summary of the findings, there is the evidence base here for further research to look at the relationship between indoor air quality, health impacts and dust behind radiators. The findings should be taken in context and the risks should not be overstated. Although this literature study cannot conclusively determine a relationship between household dust from behind radiators and health impact, it can be said that radiators are a key contributor to air and dust movement in a room, and that dust has, in the literature, demonstrated a health impact on occupants.

Further research required to fully address this relationship:

- An understanding of the contents of dust behind radiators.
- A review of dust contents in the UK in various indoor environments.
- Study modelling dust movement in a room to greater precision.
- Whether all or some dust behind radiators that becomes trapped is moved, and if so, study to find out what dust is moved around the room from the radiator.
- An understanding of attributable health consequence to dust behind radiators.
- An investigation into accumulative exposures and impacts from chemicals in dust.
- Relationship between indoor air quality and hospital admissions.
- Social and financial impact study on businesses and institutions from dust in the workplace, home or hospital.
- A study investigating the impact of PM10 and ultrafine dust particles in relation with SIDS .
- A breakdown of cost per person in the UK for mild, moderate and severe asthma treatment.

References

Alshitawi, M.S., Awbi, H.B. (2011) Measurement and prediction of the effect of students' activities on airborne particulate concentration in a classroom. *HVAC&R Research.* **17**(4), 446-464.

Asthma UK, 2016. *Animals and Pets.* [Online]
Available at: https://www.asthma.org.uk/advice/triggers/animals-and-pets/
[Accessed 8 February 2018].

Asthma uk. (2017) Asthma UK Data Portal. Retrieved28 November, 2017, from https://data.asthma.org.uk/SASVisualAnalyticsViewer/VisualAnalyticsViewer_guest.jsp?reportName=Asthma UK data portal

Athanasakis, E., Karavasiliadou, S. & Styliadis, I., 2011. The factors contributing to the risk of sudden infant death syndrome. *Hippokratia,* **15**(2), pp. 127 - 131.

Awbi, H.B. (2017) Ventilation for good indoor air quality and energy efficiency. *Energy procedia.* **112**, 227-286.

Barberán, A., Dunn, R.R>, Reich, B.J., Pacifici, K., Laber, E.B., Menninger, H.L., Morton, J.M., Henley, J.B., Leff, J.W., Miller, S.L., Fierer, N. (2015) The ecology of microscopic life in household dust. *Proc. R. Soc. B.* **282**. Doi: 10.1098/rspb.2015.1139

Batterman, S.A., Burge, H. (1995) HVAC Systems As Emission Sources Affecting Indoor Air Quality: A Critical Review. *HVAC&R Research.* **1**(1), 61-78.

Baxi, S.N., Protnoy, J.M., Larenas-Linnemann, D., Phipatanakul, W. (2016) Exposure and Health Effects of Fungi on Humans. *Journal of Allergy and Clinical Immunology: In Practice.* **4**(3), 396-404.

Behar, C., Chiu, L.F. (2013) Ventilation in energy efficient UK homes: A user experience of innovative technologies. *ECEEE Summer Study Proceedings.* DOI: 10.13140/2.1.3302.2728

Bornehag, C., Sundell, J., Weschler, C.J., Sigsgaard, T., Lundgren, B., Hasselgren, M., Hägerhed-Engman, L. (2004) The Association between Asthma and Allergic Symptoms in Children and Phthalates in House Dust: A Nested Case-Control Study. *Environmental Health Perspectives.* **112**(14), 1393-1397.

Briassoulis, G., Narlioglou, M., Hatzis, T. (2001) Toxic encephalopathy associated with the use of DEET insect repellents: A case analysis of its toxicity in children. *Human & Experimental Toxicology.* **20**, 8-14.

British Lung Foundation, 2016. *The battle for breath: the impact of lung disease in the UK,* s.l.: British Lung Foundation, ;.

Brough, H.A., Liu, A.H., Sicherer, S., Makinson, K., Douiri, A., Brown, S.J., Stephens, A.C., McLean, W.H.I., Turcanu, V., Wood, R.A., Jones, S.M., Burks, W., Dawson, P., Stablein, D., Sampson, H., Lack, G. (2015). Atopic dermatitis increases the effect of exposure to peanut antigen in dust on peanut sensitization and likely peanut allergy. J*ournal of Allergy & Clinical Immunology.* **135**(1), 164-170.

Brough, H.A., Santos, A.F., Makinson, K., Penagos, M., Stephens, A.C., Douiri, A., Fox, A.T., Toit, G.D., Turcanu, V., Lack, G. (2013) Peanut protein in household dust is related to household peanut consumption and is biologically active. *Journal of Allergy & Clinical Immunology.* **132**(3), 630-638.

Bulińska, A., Popiotek, Z., Buliński, Z. (2014) Experimentally validated CFD analysis on sampling region determination of average indoor carbon dioxide concentration in occupied space. *Building and Environment.* **72**, 319-331.

Chen, X., Li, A., Gao, R. (2012) Effects of near-wall heat source on particle deposition. *Building Simulation.* **5**, 371-382.

Chouaid, C. et al., 2004. The costs of asthma in France: an economic analysis by a Markov model. *Revue des Maladies Respiratories,* **21**(3 Pt 1), pp. 493 - 499.

Cisternas, M. G. et al., 2003. A comprehensive study of the direct and indirect costs of adult asthma.. *The Journal of Allergy and Clinical Immunology,* **111**(6), pp. 1212 - 1218.

Dancer, S. J., 2009. The role of environmental cleaning in the control of hospital-acquired infection. *The Journal of Hospital Infection,* **73**(4), pp. 378-385.

Dancer, S. J., 2014. Controlling Hospital-Acquired Infection: Focus on the Role of the Environment and New Technologies for Decontamination. *Clinical Microbiology Review,* **27**(4), pp. 665 - 690.

Dannemiller, K.C., Gent, J.F., Leaderer, B.P., Peccia, J. (2016) Influence of housing characteristics on bacterial and fungal communities in homes of asthmatic children. *Indoor Air.* **26**(2), 179-192.

Davis, S., 2008. Considering Green Heating Options. In: *Your Eco-Friendly Home: Buying, Building or Remodeling Green.* s.l.:AMACOM Division of American Managment Association, pp. 183 - 186.

Derbez, M., Berthineau, B., Cochet, V., Lethrosne, M., Pignon, C., Riberon, J., Kirchner, S. (2014) Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Building and Environment.* **72**, 173-187.

Douwes, J., Throne, P., Pearce, N., Heederik, D. (2003) Bioaerosol Health Effects and Exposure Assessment: Progress and Prospects . *Annals of Occupational Hygiene.* **37**(3), 187-200.

Ege, M.J., Mayer, M., Normand, A., Genuneit, J., Cookson, W.O.C.M., Braun-Fahländer, C., Heederik, D., Piarroux, R., Mutius, E. (2011) Exposure of Environmental Microorganisms and Childhood Asthma. *The New England Journal of Medicine.* **364**(8), 701-709.

Fleetcroft, R. et al., 2016. Emergency hospital admissions for asthma and access to primary care: cross-sectional analysis. *British Journal of General Practice,* **66**(650), pp. 640 - 646.

Fox, A.T., Sasieni, P., Du Toit, G., Syed, H., Lack, G. (2009) Household peanut consumption as a risk factor for the development of peanut allergy. *J Allergy Clin Immunol.* 123, 417-423.

Fujimura, K.E., Johnson, C.C., Ownby, D.R., Cox, M.J., Brodie, E.L., Havstad, S.L., Zoratti, E.M., Woodcroft, K.J., Bobbitt, K.R., Wegienka, G., Boushey, H.A., Lynch, S.V. (2010) Man's best friend? The effect of pet ownership on house dust microbial communities. *Journal of Allergy & Clinical Immunology.* **126**(2), 410-412.

Fujimura, K.E., Johnson, C.C., Ownby, D.R., Cox, M.J., Brodie, E.L., Havstad, S.L., Zoratti, E.M., Woodcroft, K.J., Bobbitt, K.R., Wegienka, G., Boushey, H.A., Lynch, S.V. (2010) Man's best friend? The effect of pet ownership on house dust microbial communities. *Journal of Allergy & Clinical Immunology.* **126**(2), 410-412.

Golkarffard, V., Talebizadeh, P. (2014) Numerical comparison of airborne particles deposition and dispersion in radiator and floor heating systems. *Advanced Powder Technology.* **25**, 389-397.

Griffith, C. J. et al., 2000. An evaluation of hospital cleaning regimes and standards.. *Journal of Hospital Infection,* **45**(1), pp. 19 - 28.

Gupta, R., Sheikh, A., Strachan, D.P., Anderson, H.R. (2016) Time trends in allergic disorders in the UK. *Thorax.* **62**, 91-96.

Hamilton, I., Milner, J., Chalabi, Z., Das, P., Jones, B., Shrubsole, C., Davies, M., Wilkinson, P. (2015) Health effects of home energy efficiency interventions in England: a modelling study. *BMJ Open.* **5**, e007298. Doi:10.1136/bmjopen-2014-007298

Hankin, C. S. et al., 2013. Estimated Prevalence and Economic Burden of Severe, Uncontrolled Asthma in the United States. *Journal of Allergy and Clinical Immunology,* 131(2).

Harrad, S., Hazrati, S., Ibarra, C. (2006) Concentrations of Polychlorinated Biphenyls in Indoor Air and Polybrominated Diphenyl Ethers in Indoor Air and Dust in Birmingham, United Kingdom: Implications for Human Exposure. *Environmental Science & Technology.* **30**, 4633-4638.

Hatch, D., 2014. A tale of two climates – the Netherlands and southern England compared. *Weather,* **69**(2), pp. 44 - 50.

Healthcare Commission (2005) A snapshot of hospital cleanliness in England, December, 2005. *Healthcare Comission.* [Online] Available at: <http://news.bbc.co.uk/1/shared/bsp/hi/pdfs/15_12_05_hospital_cleanliness_snapshot.pdf> [accessed 02 December 2018].

HEI (2011) Unannounced Inspection Report: Southern General Hospital | NHS Greater Glasgow and Clyde. *Healthcare Environment Inspectorate. Healthcare Improvement Scotland.* [Online] Available at: <http://healthcareimprovementscotland.org/his/idoc.ashx?docid=df08f2b9-51d5-4a5b-9aa8-466526b39a70&version=-1 > [accessed 02 January 2018].

Howdeshell, K.L., WIlson, V.S., Furr, J., Lambright, C.R., Rider, C.V., Blystone, C.R., Hotchkiss, A.K., Gray, L.E. (2008) A mixture of Five Phthalate Esters Inhibits Fetal Testicular Testosterone Production in the Sprague-Dawley Rat in a Cumulative, Dose-Additive Manner. *Technological Sciences.* **105**(1), 153-165.

Howieson, S. (2014) Are our homes making us ill? The impact of energy efficiency on indoor air quality. *Perspectives in Public Health.* **134**(6), 318-319.

Jones-Otazo, H.A., Clarke, J.P., Diamond, M.L., Archbold, J.A., Ferguson, G., Harner, T., Richardson, G.M., Ryan, J.J., Wilford, B. (2005) Is House Dust the Missing Exposure Pathway for PBDEs? An Analysis of the Urban Fate and Human Exposure to PBDEs. *Environmental Science & Technology.* **39**(14), 5121-5130.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C., Engelmann, W.H. (2001) The national human activity pattern survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology.* **11**, 231-252.

Knudsen, H.N., Andersen, R.K., Hanse, A>R., Gram-Hanssen, K. (2016) House Owners' Interests and Actions in Relation to Indoor Temperature, Air Quality and Energy Use. In *CLIMA 2016 - Proceedings of the 12th REHVA World Congress (Vol. 6).* Aalborg University.

Kubwabo, C., Fan, X., Rasmussen, P.E., Wu, F., Kosarac, I. (2016) Expanding the number of phthalates monitored in house dust. *International Journal of Environmental Analytical Chemistry.* **96**(7), 667-681.

Langer, S., Bekö, G., Bloom, E., Widheden, A., Ekberg, L. (2015) Indoor air quality in passive and conventional new houses in Sweden. *Building and Environment.* **93**, 92-100.

Larsen, K. et al., 2016. The Annual September Peak in Asthma Exacerbation Rates Still a Reality: Still a Reality ?. *Annals of the American Thoratic Society,* **13**(2), pp. 231 - 239.

Lax, S., Smith, D.P., Hampton-Marcell, J., Owens, S.M., Handley, K.M., Scott, N.M., Gibbons, S.M., Larsen, P., Shogan, B.D., Weiss, S., Metcalf, J.L., Ursell, L.K., Vázquez-Baeza, Y., Treuren, W.V., Hasan, N.A., Gibson, M.K., Colwell, R., Dantas, G., Knight, R., Hilbert, J.A. (2014) Longitudinal analysis of microbial interaction between humans and the indoor environment. *Science.* **345**(6200), 1048-1051.

Leeds Community Healthcare NHS Trust, 2014. *Infection Prevention and Control Specification for the standard of cleanliness in General Practice,* s.l.: Leeds Community Healthcare NHS Trust.

Lu, W., Howarth, A.T., Jeary, A.P. (1997) Prediction of Airflow and Temperature Field in a Room with Convective Heat Source. *Building and Environment.* **32**(6), 541-550.

Meeker, J.D., Stapleton, H.M. (2010) House Dust Concentrations of Organophosphate Flame Retardants in Relation to Hormone Levels and Semen Quality Parameters. *Environmental Health Perspectives.* **118**(3), 318-323.

Met Office (2016) Winter 2014/15. *Met Office.* [Online] Available at: <https://www.metoffice.gov.uk/climate/uk/summaries/2015/winter> [accessed 10 December 2017].

Met Office, 2017. *UK actual and anomaly maps.* [Online]
Available at: https://www.metoffice.gov.uk/climate/uk/summaries/anomacts
[Accessed 8 January 2018].

Mitro, S.D., Dodson, R.E., Singla, V., Adamkiewicz, G., Elmi, A.F., Tilly, M.K., Zota, A.R. (2016) Consumer Product Chemicals in Indoor Dust: A Quantitative Meta-analysis of U.S. Studies. *Environmental Science & Technology.* **50**, 10661-10672.

Mukherjee, M. et al., 2016. The epidemiology, healthcare and societal burden and costs of asthma in the UK and its member nations: analyses of standalone and linked national databases. *BMC Medicine,* **14**(133), pp. 1-15.

Munde, S., 2017. Working to stop asthma attacks and find a cure. *Journal of Community Nursing,* **31**(1), pp. 12 - 13.

National Patient Safety Agency, 2010. *The national specifications for cleanliness in the NHS: Guidance on setting and measuring performance outcomes in primary care medical and dental premises,* s.l.: NHS.

Nevas, M. et al., 2005. Infant Botulism Acquired from Household Dust Presenting as Sudden Infant Death Syndrome. *The Journal of Clinical Microbiology ,* **43**(1), pp. 511 - 513.

NHS (2007) The national specifications for cleanliness in the NHS: a framework for setting and measuring performance outcomes April 2007. *NHS: National Patient Safety Agency.* [Online] Available at: <http://www.nrls.npsa.nhs.uk/resources/?EntryId45=59818> [accessed 02 January 2018].

NHS Digital, 2014. *Asthma emergency admissions: fall in August, rise in September.* [Online] Available at: http://content.digital.nhs.uk/article/4989/Asthma-emergency-admissions-fall-in-August-rise-in-September
[Accessed 2014 February 2018].

NHS Estates, 2002. *Infection Control in the Built Environment guidelines,* s.l.: s.n.

NHS Yorkshire and the Humber, n.d. *Asthma: Better for Less,* s.l.: National Health Service.

NHS.uk, 2014. *Asthma is still a "killer," report warns.* [Online]
Available at: https://www.nhs.uk/news/heart-and-lungs/asthma-is-still-a-killer-report-warns/
[Accessed 13 February 2018].

NHS: National Patient Safety Agency, 2010. *The national specifications for cleanliness: Guidance on setting and measuring performance outcomes in care homes,* s.l.: NHS.

NHS: Royal United Hospital Bath, 2009. *Cleaning Procedure Manual.* [Online]
Available at:
http://www.ruh.nhs.uk/about/policies/documents/procedures/Cleaning_Procedure_Manual.pdf
[Accessed 20 February 2018].

Ouyang, X., Weiss, J.M., Boer, J. Lamoree, M.H., Leonards, P.E.G. (2017) Non-target analysis of household dust and laundry dryer lint using comprehensive two-dimensional liquid chromatography coupled with time-of-flight mass spectrometry. *Chemosphere.* **166**, 431-437.

Ownby, D. & Johnson, C. C., 2016. Recent Understandings of Pet Allergies. *F1000 Research,* pp. 1 - 9.

Rintala, H., Pitkaranta, M., Toivola, M., Paulin, L., Nevalainen, A. (2008) Diversity and seasonal dynamics of bacterial community in indoor environment. *BMC Microbiology.* **8**(56) doi:10.1186/1471-2180-8-56.

Rook, G.A. (2013) Regulation of the immune system by biodiversity from the natural environment: An ecosystem service essential to health. *PNAS.* **110**(46), 18360-18367.

Salo, P.M., Arbes, S.J., Sever, M., Jaramillo, R., Cohn, R.D., London, S.J., Zeldin, D.C. (2006) Exposure to *Alternaria alternata* in US homes is associated with asthma symptoms. *Journal of Allergy and Clinical Immunology.* **118**(4), 892-898.

Samet, J.M., Bahrami, H., Berhane, K. (2016) Indoor Air Pollution and Cardiovascular DIsease: New Evidence From Iran. *Circulation.* **133**, 2342-2344.

Singla, V. (2016) *Not Just Dirt: Toxic Chemicals in Indoor Dust.* NRDC. [Online] Available at: <https://www.nrdc.org/resources/not-just-dirt-toxic-chemicals-indoor-dust> [accessed 30 November 2017].

Strid, J., Hourihane, J., Kimber, I., Callard, R., Strobel, S. (2004) Disruption of the stratum corneum allows potent epicutaneous immunization with protein antigens resulting in a dominant systemic Th2 response. *Eur J Immunol*. **34**, 2100-2109.

Suijkerbuijk, A. W. et al., 2013. Societal costs of asthma, COPD and respiratory allergy in the Netherlands. *Nederlands Tijdschrift Voor Geneeskunde,* **157**(46), pp. 1 - 108.

Täubel, M/. Rintala, H., Pitkäranta, M., Paulin, L., Laitinen, S., Pekkanen, J., Hyvärinen, A., Nevalainen, A.(2009) The occupant as a source of house dust bacteria. *Journal of Allergy & Clinical Immunology.* **124**(4), 834-840.

Taylor, J., Mavrogianni, A., Davies, M., Das, P., Shrubsole, C., Biddulph, P., Oikonomou, E. (2015) Understanding and mitigating overheating and indoor $PM_{2.5}$ risks using coupled temperature and indoor air quality models. *Building Services Engineering Research and Technology.* **36**(2), 275-289.

Teare, E. L., Corless, D. & Peacock, A., 1998. Clostridium difficile in district general hospitals. *The Journal of Hospital Infection,* **39**(3), pp. 241 - 242.

Tham, K.W. (2016) Indoor air quality and its effects on humans - A review of challenges and developments in the last 30 years. *Energy Buildings.* **130**, 637-650.

The Hillingdon Hospitals NHS Foundation Trust, 2011. *Dust Mite Allergy.* [Online]
Available at:
https://www.thh.nhs.uk/documents/_Patients/PatientLeaflets/paediatrics/allergies/PI018-Dust_Mite_Allergy_A4_May13.pdf
[Accessed 12 February 2018].

The World Bank, 2018. *Population Estimates and Projections.* [Online]
Available at: http://databank.worldbank.org/data/reports.aspx?source=population-estimates-and-projections
[Accessed 21 February 2018].

Tong, S. & Colditz, P., 2004. Air pollution and sudden infant death syndrome: a literature review.. *Paediatric Perinatal Epidemology,* **18**(5), pp. 327 - 335.

Uzoigwe, J.C., Prum, T., Bresnahan, E., Garelnabi, M. (2013) The Emerging Role of Outdoor and Indoor Air pollution in Cardiovascular Disease. *North American Journal of Medical Sciences.* **5**(8), 445-453.

Van Der Heide, S. et al., 1997. Seasonal differences in airway hyperresponsiveness in asthmatic patients: relationship with allergen exposure and sensitization to house dust mites. *Clinical and Experimental Allergy,* **27**(6), pp. 627 - 633.

Vasile, V., Petran, H., Dima, A., Petcu, C. (2016) Indoor air quality - a key element of the energy performance of the buildings. *Energy Procedia.* **96**, 277-284.

Wang J., Li Z., Wang R., Xu Q., Tian W., Li M. (2017) Numerical Analysis of Air Flow Around a Hot Water Radiator for Its Structure Improvement. In: Zhang X., Dincer I. (eds) Energy Solutions to Combat Global Warming. Lecture Notes in Energy, vol 33. Springer, Cham [Online] Available at: <https://books.google.co.uk/books?id=cPFGDQAAQBAJ&pg=PA435&lpg=PA435&dq=Numerical+Analysis+of+Air+Flow+Around+a+Hot+Water+Radiator+for+Its+Structure+Improvement&source=bl&ots=nuZfMoGGdv&sig=6ZlWD6aGbm00sk2vKnBmf8WajSQ&hl=en&sa=X&ved=0ahUKEwi74-jrx9TXAhVKPhQKHRLMAKAQ6AEIMDAB#v=onepage&q=Numerical%20Analysis%20of%20Air%20Flow%20Around%20a%20Hot%20Water%20Radiator%20for%20Its%20Structure%20Improvement&f=false> [accessed 28/11/2017].

Weichenthal, S., Dufresne, A., Infante-Rivard, C., Joseph, L. (2007) Indoor ultrafine particle exposures and home heating systems: A cross-sectional survey of Canadian homes during the winter months. *Journal of Exposure Science and Environmental Epidemiology.* **17**, 288-297.

Witteman, A.M., van Leeuwen, J., van der Zee, J., Aalberse, R.C. (1995) Food allergens in house dust. *Int. Arch Allergy Immunol.* **107**, 566-568.

World Health Organization: International Workshop Report, 1988. Dust mite allergens and asthma: a worldwide problem. *Bulletin of the World Health Organization,* **66**(6), pp. 769 - 780.

World Health Organization, 2017. *Asthma.* [Online]
Available at: http://www.who.int/mediacentre/factsheets/fs307/en/
[Accessed 5 February 2018].

Zhang, H., Yolton, K., Webster, G.M., Sjödin, A., Calafat, A.M., Dietrich, K.N., Xi, Y., Xie, C., Braun, J.M., Lanphear, B.P., Chen, A. (2017) Prenatal PBDE and PCB Exposures and Reading, Cognition and Externalizing Behaviour in Children. *Environmental Health Perspectives.* **125**(4), 746-752.