Effective Indoor Air Quality for Energy Efficient Homes: A Comparison of UK Rating Schemes

Abstract

The use of sustainable assessment methods in the UK is on the rise, anticipating the future regulatory trajectory towards *zero carbon* by 2016. The indisputable influence of sustainable rating tools on UK building regulations conveys the importance of evaluating their effectiveness in achieving true sustainable design, without adversely effecting human health and wellbeing. This paper reviews indoor air quality issues addressed by UK sustainable assessment tools, and the potential trade-offs between building energy conservation and indoor air quality. The barriers to effective adoption of indoor air quality strategies are investigated, including recommendations, suggestions and future research needs. The review identified a fundamental lack of indoor air quality criteria in sustainable assessment tools aimed at the residential sector. The consideration of occupants' health and wellbeing should be paramount in any assessment scheme, and should not be overshadowed or obscured by the drive towards energy efficiency. A balance is essential.

Keywords: Sustainable Assessment Tools, Indoor Air Quality, Sustainability Criteria, Energy Efficient Homes, UK Eco-Homes, Zero Carbon

1. Introduction

Since the introduction of BREEAM in 1990, considerable attention has been given to the development of environmental rating tools for use within the construction industry (Lee 2012). These tools provide the opportunity to assess projects' environmental performance through criterion regarding the balance between the environment, energy, ecology and social and technological issues (Clements-Croome 2004). With the utilisation of these assessment methods still currently on the rise, it is important to evaluate their effectiveness in addressing building performance, while recognising the trade-offs between human and ecological health (Levin 2005).

These trade-offs are now particularly important in the current building industry as research suggests building design strategies aimed at tackling the effects of climate change may have a negative impact on indoor air quality (IAQ) (Yu and Crump 2010; Crump, Dengel, and Swainson 2009; Alvarez et al. 1996). For example, the drive towards increased levels of air-tightness in homes can be potentially dangerous if toxic finishes and materials are not avoided internally. This position is supported by Boyd (2010), who states that the air quality in an energy efficient, airtight home may be worse compared to a leaky one, due to the potential for build-up of indoor air pollutants.

The drive towards energy efficiency may be unintentionally and inadvertently creating unhealthy living environments; through the generation of moisture problems, increased use of toxic materials, reduction of ventilation rates, tightening of building envelopes and an over-reliance of elaborate technologies (Crump, Dengel, and Swainson 2009; Carroon 2010; Wasley 2000). As suggested by Clausen et al. (2011, p.222) in *Reflections on the state of research*, important research questions include: 'how can we ensure that IEQ [indoor environmental quality] goals are met as energy consumption to operate buildings is reduced?' Furthermore, Clausen et al. (2011) suggest the need for closer co-operation with green building councils to increase the awareness of indoor environmental quality and the effectiveness of meeting these needs in certification methods.

2. Background

Building environmental assessment methods can be categorised as either qualitative (such as BREEAM and LEED) or quantitative (such as life cycle assessment tools) (Reijnders and van Roekel 1999; El shenawy and Zmeureanu 2013) and organised by outcome as either rating tools (building performance presented in stars) or assessment tools (quantitative indicators of performance) (Ding 2008). Tools can be single criteria or multi-criteria and designed for specific building types such as offices, commercial, healthcare, or residential (Ng, Chen, and Wong 2013). The scope of this study is confined to assessment and/or rating tools for residential buildings, with a particular emphasis on the UK context. The findings from this study however are applicable to other regions since versions of BREEAM, LEED and Passivhaus are utilised worldwide (Lee 2013; Cole 2006). Furthermore, most international building assessment schemes were developed with close reference to the UK BREEAM or American LEED scheme; such as HK-BEAM and GREENSTAR (Ding 2008; Lee 2013; Cole 2006; Alyami and Rezgui 2012).

This study compares indoor air quality criteria addressed by building environmental assessment schemes; a topic of specific relevance with regards to the current sustainable building industry. Previous comparison studies have been conducted on numerous tools to measure sustainability; such as sustainability indicators (Singh et al. 2012), Life Cycle Assessment tools (Forsberg and von Malmborg 2004), and building environmental assessment schemes (Lee 2013; Alyami and Rezgui 2012; Nguyen and Altan 2011). However, most studies of building environmental assessment schemes have focused on energy evaluation and carbon emissions (Ng, Chen, and Wong 2013; Lee 2012; Lee and Burnett 2008; Roderick et al. 2009). Similar studies comparing indoor air quality are considerably lacking.

General reviews and cross comparison studies have been conducted which focus on macroscopic aspects of building environmental assessment schemes, such as characteristics, roles, structure and scope (Ding 2008; Cole 1998; Crawley and Aho 1999; Tam, Tam, and Tsui 2004; Haapio and Viitaniemi 2008). Furthermore, numerous comparison studies have been conducted on weighting methodology, credit scales and performance criteria (Todd et al. 2001; Singh et al. 2012; Lee and Burnett 2008); while others focused on particular contexts, such as construction activities (Tam, Tam, and Tsui 2004) or neighbourhood assessment schemes (Sharifi and Murayama 2013; Haapio 2012).

A limited number of studies have investigated indoor air quality criteria addressed by qualitative sustainable rating tools. Yu and Kim (2011) conducted a review of sustainable assessment methods for rating of indoor environmental quality; however emphasis was placed on commercial buildings typical of East-Asia as opposed to UK dwellings. Moreover, a cross comparison of IAQ criteria addressed by rating tools was not conducted. A comparison of IAQ criteria addressed by rating tools was however conducted by Persilly and Emmerich (2010), although the study compared sustainable guidance documents, standards, legislation and rating schemes in a U.S. context (specifically 'Standard 62.1', 'Standard 189.1', 'LEED 2009', 'GBI01', 'IGCC PV2 (draft)' and 'Federal Construction Guide').

Importantly, similar studies have rarely considered specific criterion but have instead grouped and summarised factors together as categories, such as 'indoor air quality' or 'thermal comfort'. This however does not provide adequate detail to assess the relevance of specific or individual criterion and how they compare with other assessment schemes. Furthermore, the scope and coverage of particular schemes with regards to indoor air quality has not been sufficiently addressed. This review therefore seeks to provide the opportunity to evaluate and compare criterion addressed by sustainable assessment schemes for the residential sector, presenting a summary of strategies for indoor air quality and offering recommendations and suggestions to improve the effectiveness of sustainable assessment methods at addressing indoor air quality.

3. Methods

The aim of this paper is to identify and compare the extent to which indoor air quality is considered in sustainable assessment schemes designed for the UK housing sector. The following research questions were addressed: (i) Is indoor air quality adequately considered, and if not, (ii) What factors are hindering the application of practical indoor air quality criteria in these schemes. This was achieved through a detailed cross-comparison of the existing rating schemes (specifically LEED for Homes, BREEAM Multi Residential, BREEAM Domestic Refurbishment, BREEAM EcoHomes, Passivhaus and Code for Sustainable Homes); and the identification of barriers and solutions to the effective adoption of indoor air quality criteria. Relevant literature is considered, in addition to current guidelines and legislations.

Firstly, an in-depth review of the sustainable assessment scheme documents was conducted in order to identify criteria relating to indoor air quality. The following scheme documents were examined: Code for Sustainable Homes Technical Guide, 2010 (DCLG 2010a), BREEAM Refurbishment Domestic Buildings Technical Manual SD5072-2012-1.0.2 (BRE 2012), EcoHomes 2006- The Guidance- Issue 1.2 (BRE 2006), BREEAM Multi-Residential 2008 Scheme Document SD 5064 (BRE 2012), LEED for homes v2008 (USGBC 2010) and The Passive House Planning Package (PHPP) Version 7 (2012) (Feist et al. 2012).

Criteria relating to indoor air quality were initially listed for each sustainable assessment scheme, which was then summarised under headings to allow for comparison between schemes, as illustrated in Table 1. An analysis framework based on emerging themes was then formulated and utilised for a detailed cross-comparison of particular indoor air quality issues addressed by the sustainable assessment methods. This is followed by a review of barriers and solutions to the adoption of effective indoor air quality criteria and conclusions. The research methodology is illustrated in Figure 1.

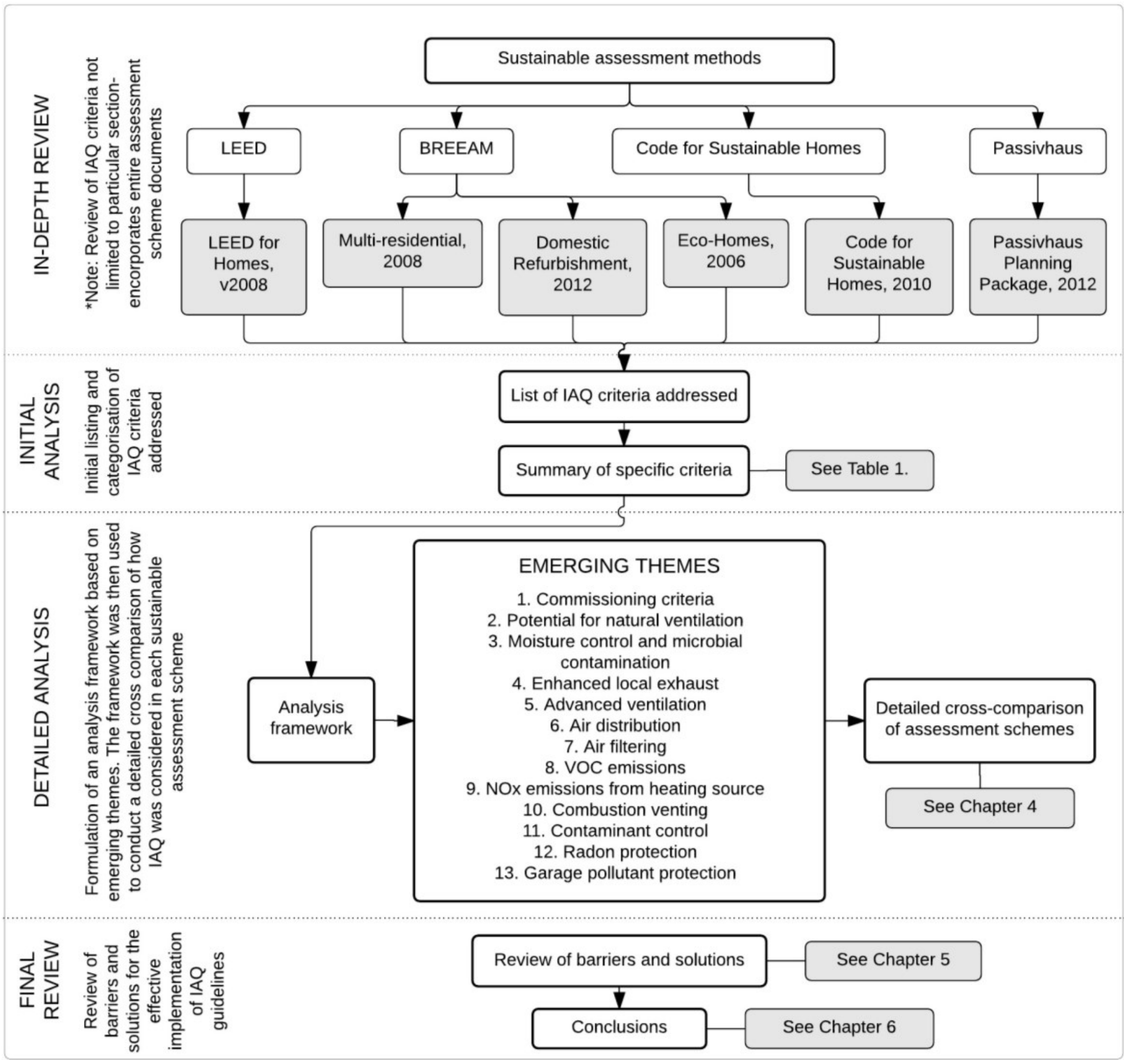

Figure 1. The research methodology

4. Results and Discussion

4.1. Review of indoor air quality criteria in UK rating schemes

The following review of IAQ issues is not limited to one particular section; rather incorporates the entire building energy code. For instance, IAQ is associated not only with indoor environmental quality and/or health and wellbeing, but also encompasses issues relating to building materials, pollution, management and energy. Thus a holistic, comprehensive approach is required.

Table 1: Comparison of indoor air quality criteria in UK domestic rating schemes

IAQ Issues	BREEAM Multi-Residential	BREEAM Domestic Refurb.	BREEAM Eco-Homes	CSH's	Passivhaus Standard	LEED
Commissioning manager appointed for ventilation systems	✓	×	×	×	×	×
Post occupancy evaluation of ventilation strategy	✓	×	×	×	×	×
Performance testing of ventilation	✓	×	×	×	✓	✓
Encouragement of natural ventilation	✓	×	×	×	×	×
Enhanced local exhaust	×	×	×	×	×	✓
Third party testing of local exhaust	×	×	×	×	×	✓
Positioning intake vents away from pollution sources	✓	×	×	×	×	×
Building user guide providing information on IAQ	Limited	Limited	Limited	Limited	×	Limited
Reduction of NOx emissions	✓	✓	✓	✓	×	×
Enhanced combustion venting	×	×	×	×	×	✓
CO detectors installed	×	✓	×	×	×	✓
Specification of no/low emitting products	✓	✓	×	×	×	✓
Specification of no/low emitting building furnishings	×	×	×	×	×	×
Criteria for prevention of legionaires disease	✓	×	×	×	×	×
Measures for radon prevention	×	×	×	×	×	✓
Pre-occupancy flush	×	×	×	×	×	✓
Moisture control	×	×	×	×	×	✓
Enhanced ventilation	×	✓	×	×	✓	✓
Air filtering	×	×	×	×	✓	✓
Contaminant control during construction	×	×	×	×	×	✓
Indoor contaminant control features	×	×	×	×	×	✓
Garage pollutant protection	×	×	×	×	×	✓
Physical IAQ measurements	×	×	×	×	×	×
Total	8/23	4/23	1/23	1/23	3/23	13/23

It should be noted, the category 'Indoor Environmental Quality' (IEQ) in LEED provides users with two possible pathways for accreditation; either with or without use of the Energy Star rating system. For the purpose of this research, pathway two (EQ2 -

EQ10) will be investigated, which does not use the Energy Star rating system.

4.1.1. *Commissioning criteria*

Table 2: Commissioning criteria credits

Scheme	Criteria relating to IAQ	Credits	Minimum Standard
BREEAM Multi-residential	A specialist commissioning manager is appointed (during design stage) for complex systems such as: air conditioning, mechanical ventilation, displacement ventilation, complex passive ventilation	1	Yes
	For complex systems- Testing of all building services under full and part load (seasonal) conditions, and during periods of extreme occupancy (where applicable). Interviews with occupants (where affected) to identify problems or concerns. For simple systems (naturally ventilated)- review thermal comfort, ventilation, and lighting (by measurements or occupant feedback) and take reasonable steps to re-commission after review	1	Yes

The commissioning of mechanical ventilation systems is essential to ensure performance, yet recent evidence indicates that inadequate commissioning is common (Sullivan et al. 2013). Despite this, BREEAM Multi-residential is the only scheme to address this issue, as illustrated in Table 2. One credit is awarded for the appointment of a specialist commissioning manager during design stage for complex ventilation systems. This should help reduce the risk of typical problems, such as poor installation and performance, lack of transparency to building occupants and increased sensitivity to deviations from design assumptions (Leyten and Kurvers 2006).

Furthermore, the testing of complex ventilation systems under full load conditions may identify potential indoor air quality problems sooner. For naturally ventilated buildings, a review of thermal comfort, ventilation and lighting is required at three, six and nine months after initial occupation. It is suggested that IAQ measurements should also be included in the evaluations, particularly during typical occupancy conditions.

4.1.2. *Building user guide and training*

Table 3: Credits for building user guide and training

Scheme	Criteria relating to IAQ	Credits	Minimum Standard
BREEAM Multi-residential	Development of building user guide, which includes information on cooling/ventilation in building and maintenance of building systems. User guide should provide info on re-fit considerations, including impact of re-positioning furniture and layout changes (i.e. may cover grilles/outlets, higher density occupation)	1	Yes
CSH's	Home user guide provided, with information on strategies/features including heat recovery systems and passive vents, maintenance requirements, sustainable DIY (the use of low VOC products)	2	No
BREEAM Domestic Refurb.	Home user guide contains recommendations for improvements, including the use of low VOC materials and/or products. Basic user instructions of technologies should also be included if appropriate, including MVHR	3	No
	Handover meeting and two or more of following: post occupancy interviews, site inspection (during first three months) and/or aftercare advice	2	No
BREEAM EcoHomes	Provision of simple guide suitable for non-technical occupant which should contain information on environmental strategies and design features, including the use of MVHR. Under the section sustainable DIY- the use of low VOC products is mentioned	2	No
LEED	Provision of a home operations and maintenance manual which includes mechanical ventilation devices and occupant activities (such as cleaning materials/supplies). Minimum one hour walkthrough of the home.	1	Yes
	Two additional hours of training	1	No

The BREEAM Multi-residential scheme awards credits for the provision of a building user guide to occupants, which covers general issues, such as the effect of changes to layout and occupancy load on ventilation; however neglects specific IAQ issues such as moisture and pollution generating activities, and use of air polluting products and materials (including paints, cosmetics, cleaning products and fragrances). Furthermore, it does not consider IAQ aspects of re-fits, such as VOC emissions. The use of low VOC products for future DIY projects is included in criteria in the Code for Sustainable Homes scheme, however this does not cover every-day pollution generating activities. Furthermore, general information on ventilation strategies, including local exhaust ventilation and/or boost mode are not specified directly.

Basic user instructions of mechanical ventilation technologies are covered in BREEAM Domestic Refurbishment and BREEAM Eco-Homes, however these are limited as they do not directly specify important issues to be addressed; such as maintenance requirements of the system. The use of low VOC products and/or materials for home improvements is addressed in both these schemes, similar to the Code for Sustainable Homes. The home user guide however in all four schemes is usually provided as a bulky, cumbersome document, which is not likely to be studied in any great detail by the building occupants. A practical introduction would be much more beneficial, providing the opportunity to ask questions and gain hands-on training of equipment and devices, ideally split over a few months. This is covered to some degree by BREEAM Domestic Refurbishment and LEED for Homes, as illustrated in Table 3.

4.1.3. Potential for natural ventilation

The potential for natural ventilation is important, particularly for purge ventilation in both mechanically and naturally ventilated homes. The only assessment scheme that addresses this issue however is BREEAM Multi-residential, which awards one credit to homes demonstrating the potential for natural ventilation. This criterion requires evidence of adequate cross flow of air in communal occupied spaces through calculations or by openable window area equivalent to 5% of the gross internal floor area. Furthermore, the natural ventilation strategy must be 'capable of providing at least two levels of user-control (…) with higher ventilation achievable to remove short-term odours' (BRE 2012, p.71). This criterion helps to deviate from the design of inoperable windows (for the purpose of increased air-tightness) in recent energy efficient strategies, which has led to issues with occupancy control. Furthermore, it provides adaption strategies aimed at reducing the risk of overheating in mechanically ventilated homes.

4.1.4. Moisture control and microbial contamination

A body of research has identified associations between exposure to microbial contaminants (as a result of excessive indoor moisture) and a multitude of illnesses, including asthma, allergies, respiratory symptoms and immunological reactions (World Health Organisation 2009). The LEED rating system aims to reduce this exposure through use of dehumidification to maintain relative humidity levels at or below 60% (USGBC 2010).

Table 4: Moisture control and microbial contamination criteria

Scheme	Criteria relating to IAQ	Credits	Minimum Standard
BREEAM Multi-Residential	Water systems designed in compliance with Health and Safety Executive's 'Legionnaires' disease- The control of legionella bacteria in water systems'. No humidification or only steam humidification specified/provided	1	Yes
LEED	Maintain relative humidity at or below 60% through use of dehumidification system or central HVAC system with a dehumidification mode.	1	No

The reduction of relative humidity levels is beneficial to reduce the proliferation of house dust mite and fungal growth, however low levels (not addressed by LEED for homes) may also have health implications; such as mucous membrane irritation, increased frequency of colds and increased discomfort (Burroughs and Hansen 2004). Additionally, the utilisation of active dehumidification is not recommended for every scheme, thus the credit is not suitable for every building (USGBC 2010).

The BREEAM Multi-Residential scheme provides criteria relating to microbial contamination; however these are limited as they only relate to the prevention of Legionnaires disease. Microbial contamination however should also cover issues such as airborne mould and bacteria. Mould prevention strategies should be included, and appropriately awarded. This is particularly important in air-tight homes where reduced infiltration can lead to increased moisture, mould and house dust mite proliferation (Ridley et al. 2006), which is associated with increased risk of developing asthma (Quansah et al. 2012).

Criterion should be awarded by building assessment schemes to encourage the removal of excess moisture from occupant activities; such as adequately vented tumble driers and effective local exhaust systems. In many air tight homes, condenser tumble-driers and recirculation cooker hoods are utilised, which eliminate the need to puncture the air-tight membrane for ductwork. The effectiveness of these systems in adequately removing pollutants and moisture from the interior environment however is debateable. Monitoring of indoor humidity levels could also be conducted to reduce the risk of mould growth and house dust mite proliferation.

4.1.5. *Enhanced local exhaust*

The LEED for Home's scheme is the only assessment method reviewed that awards criteria for enhanced local exhaust systems. BREEAM Domestic Refurbishment does however award homes that comply with extract ventilation requirements of Building Regulations Part F for the whole building, as opposed to new rooms only. As recommended by criterion EQ 5.2, the use of a sensor, timer and/or humidistat controller is an effective method to reduce excess moisture in the bathroom.

Table 5: Credits for enhanced local exhaust

Scheme	Criteria relating to IAQ	Credits	Minimum Standard
LEED	Design/install local exhaust systems in bathrooms and kitchens to section 5 ASHRAE Standard 62.2-2007, fans and ducts to section 7 ASHRAE Standard 62.2-2007, exhaust air to outside and utilise bathroom exhaust fans labelled with ENERGY STAR.	0	Yes
	Use of occupancy sensor, automatic timer, continuous exhaust fan or automatic humidistat controller in bathroom	1	No
	Third party performance testing	1	No

There is the potential however to include similar strategies for kitchens to reduce exposure to pollutants, such as an automatic local exhaust fan linked to the operation of a cooker or similar equipment. As suggested by Kim et al. (2011), emissions generated by cooking activities can be significant sources of primary indoor air pollutants, such as particulate matter, carbon monoxide and sulphur dioxide. Furthermore, greater emphasis should be placed on performance testing of ventilation systems post occupancy, to ensure effective ventilation.

4.1.6. *Advanced ventilation*

The presence of prerequisites for ventilation is essential to ensure adequate IAQ. The LEED for Homes rating system requires the design and installation of whole-house ventilation systems, continuous ventilation, intermittent ventilation, or passive ventilation to ASHRAE standard 62.2-2007. It should be noted however that this section intends to 'reduce occupant exposure to indoor pollutants by ventilating with outdoor air' (USGBC 2010, 90), which assumes outdoor air is fresh, which may not be the case in every situation. Two credits are awarded for the use of heat/energy recovery system, which should help to recover heat/energy lost through ventilated air. Only one point is awarded for third party performance testing. It could be suggested that performance testing may be more valuable and thus should be awarded accordingly. A heat recovery system and/or whole house ventilation system may fail to meet even basic ventilation requirements therefore adequate post occupancy testing is essential.

BREEAM standard for Multi Residential buildings includes a specific issue entitled 'indoor air quality', which awards criteria relating to ventilation. However, only one credit is available to buildings that demonstrate compliance. As this is not a minimum standard, a building can successfully achieve the highest BREEAM rating ('outstanding') without addressing any criteria mentioned in Table 6.

Furthermore, the recommended minimum fresh air rates are only provided for office areas; as explained by BREEAM (BRE 2012, 74), 'fresh air criteria are not specified for other areas of the building (...) as the provision of fresh air is adequately covered in Approved Document Part F (ADF) Ventilation'. Thus sufficient fresh air rates within the home environment are not awarded under the BREEAM Multi-residential scheme. The criterion also requires building intakes to be positioned at least 20 meters from external pollution sources (10 meters in naturally ventilated buildings) and 10 meters from exhausts. This should help to ensure fresh air is delivered to the interior environment.

BREEAM Refurbishment refers to Building Regulations Approved Document F which requires minimum background ventilation for new rooms and/or windows, however awards points if minimum ventilation is achieved across the whole building. Post occupancy testing and/or evaluation of ventilation however is not required, rather documentary evidence or confirmation from the developer. This is not sufficient, particularly for energy efficient homes that are mechanically ventilated as actual ventilation may vary significantly from designed ventilation.

In relation to the Passivhaus standard, reference to IAQ is limited in the PHPP (Passivhaus Planning Package) to a required average minimum Air Change Rate (ACR) of 0.3 h-1. According to various studies however, ventilation rates less than 0.5 h-1 (national standard for most European countries) have been associated with allergic symptoms (Bornehag, Sundell, and Sigsgaard 2004; Bornehag et al. 2005), proliferation of house dust mites (Wargocki et al. 2002), mould growth (Ucci et al. 2004) and perception of poor IAQ (Engvall, Wickman, and Norbäck 2005; Dimitroulopoulou 2012).

Table 6: Credits for advanced ventilation

Scheme	Criteria relating to IAQ	Credits	Minimum Standard
LEED	The design and installation of whole house ventilation system in compliance with ASHRAE Standard 62.2-2007	0	Yes
	Install heat/energy recovery system which is listed by certified testing lab or in mild climates a whole house ventilation system	2	No
	Third party performance testing of ventilation	1	No
BREEAM Domestic Refurb.	Minimum background ventilation compliant with section 7, minimum extract ventilation in wet rooms compliant with section 5 and minimum purge ventilation compliant with section 7 of Building Regulations Approved Document Part F. If historic building, compliant with the requirements for historic buildings (CN4)	1	Yes
	Ventilation compliant with section 5 of Building Regulations ADF in full or if historic building, requirements for historic buildings met.	1	No
BREEAM Multi-residential	In air conditioned/ mixed mode buildings, intakes >20m from external pollution sources and >10m apart from exhausts. In naturally ventilated buildings, ventilators/openable windows over 10m from external pollution sources. Fresh air rates in accordance to British Council- Guide to Best Practice in the Specification of Offices 0f 12 l/s per person. Building areas subject to large and/or variable occupancy patterns- Carbon dioxide or alternative air quality sensors required with warning signals and/or linked to ventilation system.	1	No
Passivhaus	Average minimum Air Change Rate (ACR) of 0.3 h-1	n/a	Yes

4.1.7. Air distribution

The LEED for Homes assessment scheme promotes sufficient distribution of space heating and cooling through room-by-room calculations and third party performance testing of total supply airflow rates. This should help to promote adequate ventilation through appropriate duct installation and sufficient supply airflow rates. Third party testing of HVAC systems post occupancy is essential to ensure adequate airflow rates are met in practice, and are awarded accordingly with 2 credits available. It may be important however to conduct regular testing of ventilation effectiveness (e.g. using a flow hood) and maintenance checks as poorly performing HVAC systems may cause IAQ problems in the future.

4.1.8. Air filtering

Research suggests airborne particulate matter generated by typical activities (such as combustion, tobacco smoking, cooking or cleaning) can cause serious health effects in humans, primarily to the cardiovascular and respiratory system (Marconi, Seifert, and Lindvall 1995). The use of Minimum Efficiency Reporting Value (MERV) of 8 or more is encouraged by LEED with the intent to 'reduce particulate matter from the air supply system' (USGBC 2010, 95), with 1 credit awarded for the use of MERV of 10 or more and 2 credits awarded to the use of MERV of 13 or more.

Table 7: MERV Comparison (adapted from (Burroughs and Hansen 2011))

EU ratings	MERV level	Original Dust Spot %	Typical Particulate Filter Type	% 0.3-1µm	% 1-3µm	% 3-10µm
G1, G2	1	NA	Low efficiency fiberglass and synthetic media disposable panels, cleanable filters, and electrostatic charged media panels	Too low efficiency to be applicable to 52.2 determination		
	2	NA				
	3	NA				
	4	NA				
G3	5	NA	Pleated filters, cartridge/cube filters, and disposable multi-density synthetic link panels			20-35
G4	6	NA				36-50
G4	7	25-30%				50-70
F5	8	30-35%				>70
F5	9	40-45%	Enhanced media pleated filters, bag filters of either fiberglass or synthetic media, rigid box filters using lofted or paper media		>50	>85
F6	10	50-55%			50-65	>85
F6	11	60-65%			65-80	>85
F6	12	70-75%			>80	>90
F7	13	80-85%	Bag filters, rigid box filters, minipleat cartridge filters	>75	>90	>90
F8	14	90-95%		75-85	>90	>90
F9	15	>95%		85-95	>90	>90
H11	16	98%		>95	>95	>95
The following classes are determined by different methodology than ASHRAE 52.2-1999						
H13	17	N/A	HEPA/ULPA filters evaluated using IEST MoT. Types A through to D yield efficiencies @ .3µm and Type F @0.1 µm	99.97% IEST Type A		
	18	N/A		99.99% IEST Type C		
H14	19	N/A		99.999% IEST Type D		
H15	20	N/A		>99.999% IEST Type F		

As illustrated in Table 7, a MERV of 8 provides a degree of protection (>70%) from particles of between 3 and 10µm in size, however is not suitable for the filtration of 0.3-3µm particles. Fine (<2.5µm) and ultrafine (<0.1µm) particles are of particular concern to health due to their ability to pentrate deep into the lower respiratory tract and deposit in alveoli or air spaces of the lungs (Yassi et al. 2001). The Passivhaus standard requires a minimum filter grade of F7 for fresh air intake, which is equivalent to an MERV level of 13. This filter grade provides an efficiency of 90% for particles sized 1-10 μm in diameter, however only 75% efficiency for particles between 0.3 and 1 μm. BREEAM Multi-residential, BREEAM EcoHomes and the Code for Sustainable Homes award no credits for the use of filters, thus inadequately address the importance of filter efficiency in mechanical ventilation systems.

As suggested by the Environmental Protection Agency (EPA) (2003) particles less than 10μm in diameter may potentially pass directly through the lungs and enter the bloodstream. Protection from particulate matter therefore is essential, particularly in heavily polluted areas. It is important to note that regular cleaning of filters is essential to ensure performance thus should be included in the awareness and education section.

4.1.9. Volatile organic compound emissions

The VOC criteria addressed by the BREEAM Multi-residential scheme covers a range of building products including wood panels, timber structures, wood flooring, resilient, textile and laminate floor coverings, wall coverings, adhesives and decorative paints and varnishes. Furnishings however are not considered. The criterion requires the testing and compliance with European Standards for VOCs, however does not consider the degree of compliance.

Furthermore, information should be provided to homeowners on VOC emissions from everyday products, such as air-fresheners, fragrances, cleaning products and glues. Consideration should also be given to maintenance of building materials/products and whether VOC emitting products are required for cleaning and preservation purposes. As illustrated in Table 8, only one credit is available for this issue, which is not required as a minimum standard.

The use of low emitting building products is encouraged in the LEED category ‘materials and resources’, with a total of 8 credits available (0.5 credit per component). The criteria also refers to various standards, such as the South Coast Air Quality Management, Green Seal and California’s practice for testing VOC emissions from building materials. Reference is also provided to various VOC standards for a range of building products, such as paints, finishers and sealers.

Table 8: Criteria for reduction of volatile organic compounds

Scheme	Criteria relating to IAQ	Credits	Minimum Standard
BREEAM Multi Residential	Testing and compliance with relevant VOC emission European Standards for specific building materials	1	No
LEED	Use of products that meet specifications for environmentally preferable products AND/OR low emissions AND/OR local production (awarded 0.5 credits per component, up to maximum of 8 credits)	8	No
BREEAM Domestic Refurb.	All decorative paints, varnishes and at least 5 of remaining 8 product categories to meet testing requirements and VOC emission levels against relevant standards. If 5 or less products specified, all must meet emissions standards.	1	No
BREEAM EcoHomes	Credits achieved if 80% of area for each element achieves an 'A' rating from the Green Guide for Housing Specification, which considers human toxicity; albeit limited.	16	No

It should be noted however that all eight credits are achievable without adhering to any emission reducing strategies through use of FSC certified, reclaimed or recycled materials. Furthermore, the rating system fails to place sufficient attention on low emission products by simply stating "products with low emissions of volatile organic compounds (VOCs) may improve indoor air quality" (USGBC 2010, 81). The rationale behind the use of low VOC products is therefore not fully elucidated.

The BREEAM Domestic Refurbishment scheme awards one credit if all decorative varnishes, paints and at least five of the remaining eight product categories (wood panels; timber structures; wood flooring; resilient, textile and laminate floor coverings; suspended ceiling tiles; flooring adhesives; wall coverings and adhesive for hanging flexible wall coverings) meet testing requirements and VOC emission levels against relevant standards. If five or less products are specified, all must meet emission standards. This criterion however does not include insulation materials or furnishings.

The BREEAM Domestic Refurbishment scheme contains a separate section entitled 'insulation' where credits are derived with reference to the green guide to specification. This guide considers human toxicity of materials; albeit limited. Due to the large surface area of insulation, it has the potential to significantly impact the quality of indoor air through off-gassing over time; particular risks include formaldehyde containing insulation and the utilisation of toxic chemicals such as flame retardants.

Similarly, the BREEAM EcoHomes scheme refers to the Green Guide for Housing Specification, which rates building elements from A (good) to C (poor). Volatile Organic Compound emissions are not considered directly; only limited consideration of overall human toxicity. The increase in interior temperatures, moisture and reduction of ventilation rates in energy efficient homes however is significantly increasing the concentration of VOCs indoors. These sustainable assessment schemes therefore fail to adequately protect the health and wellbeing of occupants due to insufficient credits and lack of minimum standards for VOCs.

4.1.10. NOx emissions from heating source

Although not primarily related to indoor air, reduction of oxides of nitrogen emissions from heating sources may help to reduce concentrations in the interior environment. All BREEAM schemes (Multi Residential, Domestic Refurbishment and EcoHomes) award up to 3 credits; 1 for NOx emissions ≤100 mg/kWh, 2 for ≤70 mg/kWh, and 3 for ≤40 mg/kWh. The reduction of emissions of nitric oxide and nitrogen dioxide will help subsequently reduce levels indoors. LEED for Home's and the Passivhaus Standard do not directly address this issue, however the Passivhaus scheme does require an annual space heating energy demand of less than 15 kWh/(m2a), which would significantly reduce emissions.

4.1.11. Combustion venting

In LEED for Homes, the prerequisite of carbon monoxide monitors on each floor, vented combustion appliances, doors on fireplaces/woodstoves and criteria for space/water heating appliances that utilise combustion provides adequate protection from combustion gases, which can be improved through adherence to additional criteria. The performance of a back draft potential test will help to further reduce the risk of leakage of combustion gases into occupied space. It may be important however to also consider guidance for secondary heating equipment such as space heaters.

The BREEAM Domestic Refurbishment scheme requires carbon monoxide and fire alarms connected to the main electricity supply (if re-wiring required) and battery back-up, which should help reduce risk of exposure to fatal levels of smoke and/or carbon monoxide. Consideration should however be given to protect occupants from combustion gases emitted from appliances, such as gas fires, stoves, space heaters, fireplaces and even gas cookers. BREEAM EcoHomes, BREEAM Multi-Residential and Code for Sustainable Homes all fail to adequately address this issue.

Table 9: Criteria for combustion venting

Scheme	Criteria relating to IAQ	Credits	Minimum Standard
LEED	All fireplaces/ woodstoves must have doors, combustion appliances must be vented, carbon monoxide monitor installed on each floor, combustion based water/space heating equipment must be designed and installed with closed combustion, power-vented exhaust or located in detached utility building/open air facility.	0	Yes
	No fireplace or woodstove installed or installed to requirements for better practice which includes installation by approved safety testing facility or to ASTM E-1602/ ASTM E 1509-04 (1 credit) or best practice which includes back draft potential test $\Delta P \leq 5$ Pascal's (2 credits).	2	No
BREEAM Domestic Refurb.	Carbon monoxide and fire detector supplied in accordance with compliance notes and powered by dwellings main electricity supply if project involves re-wiring	1	Yes

4.1.12. Contaminant control

Control of indoor contaminants is promoted only by the LEED rating scheme, through credits for various design features (such as permanent walk off mats, central vacuum system and/or shoe removal space), preoccupancy flush and sealing of ducts and vents during construction. The design features have the potential to reduce ingress of dust and dirt from outdoors, however only if used by the occupants in practice.

The preoccupancy flush helps to reduce occupant exposure to VOCs released from building products and materials and should be an important aspect of every construction project. LEED for Homes rating system recommends a period of 48 hours to flush the entire house either through opening windows and using a fan or operating HVAC and exhaust fans on the highest rate (USGBC 2010). However, advice should also be given to occupants when moving into the home to maintain high ventilation rates for a period of 2-3 weeks to reduce exposure to indoor air pollution.

4.1.13. Radon protection

Radon, a well known carcinogen present in indoor air, is an inert and noble gas formed through the decay of uranium (Spengler, Samet, and McCarthy 2001). It is suggested that energy efficient strategies such as the installation of double glazing and draft proofing may potentially increase radon levels indoors by more than 50% (Bone et al. 2010; Gunby et al. 1993). LEED however is the only assessment scheme reviewed to address this issue. LEED promotes the reduction of radon exposure through the use of radon-resistant construction techniques, as prescribed by the Washington State Ventilation and Indoor Air Quality Code, EPA, the International Residential Code or an equivalent standard (USGBC 2010). The LEED scheme requires radon resistant construction in high risk areas as a minimum standard, and awards one credit for use of moderate risk areas.

However, as suggested by LEED (USGBC 2010, 97), 'radon-resistant construction does not guarantee that occupants will not be exposed to radon'. As recommended by EPA, all homes should therefore conduct radon tests to determine the degree of exposure. LEED should incorporate this in their rating criteria to ensure the performance of radon resistant construction techniques in practice.

4.1.14. Garage pollutant protection

Garages accumulate high concentrations of various indoor air pollutants, such as particulates, carbon monoxide, VOCs, formaldehyde, nitrogen dioxide and other combustion gases. The criteria in the LEED for Homes scheme helps to reduce the ingress of pollutants from the garage into the living spaces. This is not addressed in any other assessment scheme reviewed.

Two credits are awarded in this scheme for the sealing of shared surfaces between the garage and living spaces with the installation of a carbon monoxide alarm and for the use of an exhaust fan in the garage. Care should be taken to protect occupants while in the garage and/or home as exhaust fans with automatic control (linked to for instance, a light switch or opening/closing of garage door) are acceptable for the credit. The intermittent use of an exhaust fan may not protect occupants from constant pollutant sources such as the storage of chemicals, pesticides, and/or exhaust fumes.

5. Barriers and Solutions for Effective IAQ Guidelines in Sustainable Homes

Table 10: Summary of barriers and solutions

Barriers	Solutions
Intangibility of health and problems associated with measuring quantifiable benefits	Further research needed on indoor air pollutants and associated health and wellbeing impacts
Complexity of indoor emission behaviour- variability of IAQ and problems with assessment methods	Need for a standardised comprehensive protocol for the measurement of indoor air quality in residential environments
Lack of universally accepted indoor air quality guidelines	Development of universal guidelines for major indoor air pollutants
Increase in demands for air-tightness and energy efficient ventilation strategies	Development of effective IAQ criteria in existing building energy standards and legislations. IAQ certification of building materials and products
Emphasis of design goals as opposed to performance goals	Need for more post-occupancy evaluations, particularly for IAQ, comfort and occupant health. Evaluation system where certificates and standards only achieved after 1-2 year monitoring period
Lack of knowledge integration, architect's lack knowledge on IAQ	Need for trans-disciplinary research. Translation of existing knowledge to practical design guidelines aimed at architectural and sustainable consultant professionals, further training needs
Criteria considered in isolation, which leads to *'point shopping'*(Levin, 2012)	Minimum standards needed for indoor environmental quality and a greater awareness of interconnectivity between sustainability concepts
Cost of physical indoor air quality measurements	Development of economical IAQ measurement strategy for implementation in conjunction with domestic energy codes

5.1. Barriers

One reason for the lack of attention to IAQ may be due to the intangibility of health and the problems associated with measuring quantifiable benefits. As suggested by Dols et al. (1996), references to IAQ by paradigms of sustainable building designs are often qualitative and general. This is supported by Bone et al. (2010), who suggest that rating tools are mostly weighted towards easily definable measures of water and energy use, as opposed to health.

The quality of indoor air is dependent on a multifaceted relationship between building design, maintenance, operation, environmental conditions and climate. The assessment of IAQ therefore is problematic, particularly regarding the complex amalgamation of contaminants in the interior environment, and diverse variations in the local and temporal substance spectrum (Salthammer 2011). As suggested by Persily & Emmerich (2010, p.4), ‘the large number of indoor contaminants, variations in individual susceptibility to contaminant exposure, and ultimately the lack of guideline or regulatory levels for the vast majority of contaminants make it impossible to define IAQ performance in terms of just contaminant concentrations.’ This variability can be challenging when attempting to rate or measure the quality of indoor air.

The lack of guidelines or regulatory levels for pollutants is affecting the ability to deliver robust IAQ criteria for sustainable assessment tools. As explained by Salthammer (2011), inconsistent guideline values for indoor air substances are in some cases published without any justification or verification. Harrison (2002) suggests barriers to standardised indoor air quality guidelines for the UK include issues regarding responsibility of monitoring, legal implications for exceeding guideline values, and questions over the types of building to be included.

In addition, changes in the UK Building Regulations towards more stringent demands on air-tightness (including requirements for pressure testing of new homes) will put pressure on architects and construction professionals to focus more on detailing (Ward 2008). However, as suggested by Dimitroulopoulou et al. (2005, p.11), ‘as dwellings become more airtight, sources of air pollution can have a greater impact on IAQ and occupants may experience adverse health effects’. Furthermore, trade-offs between IAQ and building energy conservation such as ventilation rates and specification of materials may be more heavily weighted to energy conservation goals.

The specific emphasis on design goals by sustainability rating tools as opposed to performance goals further affects the ability of sustainable buildings to achieve targets in practice (Dols, Persilly, and Nabinger 1996). Thus acclaimed sustainable buildings may, in reality, be no better than traditional building practices. This is particularly true when considering health and wellbeing criteria, due to the lack of post occupancy evaluations in this area. This is supported by Crump, Dengel and Swainson (2009), who suggest an urgent need for research into the impacts on health and wellbeing of highly energy efficient homes.

A further barrier to the successful adoption of IAQ strategies in sustainability rating tools is the lack of knowledge integration from indoor sciences (Levin 2005). The specialised nature of IAQ research is rarely translated into practical, comprehensive guidelines suitable to building designers and sustainable consultants. This sub-disciplinary tradition of IAQ research is a major problem, particularly as the building design is fundamental to the quality of internal air.

The fundamental framework of sustainable assessment methods promotes the trend of '*point shopping*' (Levin 2012) where inexpensive and easily obtainable credits are favoured. As suggested by Persily & Emmerich (2010, p.9), 'treating system or performance issues in isolation can contribute to less than optimal design and operation decisions that can compromise both energy efficiency and IAQ'. Sustainability in design is defined as an essential balance between economic, environmental and social issues (McGregor, Roberts, and Cousins 2012). Thus assessment methods should not permit biased attention to specific elements, such as energy efficiency. A comprehensive, holistic approach is essential.

Finally, the cost of IAQ measurements makes it difficult to set guidelines for indoor air pollutants. As suggested by Hui, Wong and Mui (2006, p.374), IAQ assessments require 'a considerable amount of resources and manpower in terms of sophisticated knowledge of application, calibration and regular maintenance of the appliances, interpretation of the data, and on-site operation of the equipment'. In order for assessment methods to be utilised widely within the building sector, consideration needs to be given to the level of difficulty in evaluation or application (Yu and Kim 2011).

In conclusion, these barriers result in a lack of comprehensive assessment methods that achieve environmentally friendly and healthy building design. There is an urgent need for an improvement of current systems through the development of effective IAQ criteria to counteract the trade-offs associated with specific energy efficient design strategies. The following section presents potential solutions to these barriers.

5.2. Solutions

A comprehensive understanding of causal relationships between major indoor air pollutants and building related illnesses remains incomplete, despite numerous studies on IAQ and health (Clausen et al. 2011; Mendell et al. 2002; Nøjgaard, Christensen, and Wolkoff 2005). Further research is required to investigate the benefits of improved IAQ on occupant health and wellbeing in order to highlight the fundamental importance of healthy building design within the construction industry. As suggested by Dales et al. (2008), an enhanced understanding of the link between IAQ and health has the potential to benefit the health of not only vulnerable members of society, but the entire population.

In order to examine the links between IAQ and health, a standardised comprehensive protocol is required. At present, British and European standards exist for the measurement of numerous indoor air pollutants such as VOCs, formaldehyde, asbestos, carbon dioxide, nitrogen dioxide and mould. There remains a need however for a simplified, systematically rigorous and functionally feasible IAQ measurement protocol (Chao, Chan, and Ho 2001). This will also require the development of universal guidelines for all major indoor air pollutants.

There is a need also for the incorporation of effective IAQ criteria in existing building energy codes and standards. For instance, Energy Performance Certificates (EPC's) should be utilised in correspondence with IAQ guidelines in the UK, to ensure one is not sacrificed for the other. These criteria should be based on performance goals, as opposed to design goals. Building energy assessment methods therefore should be awarded after a 1-2 year monitoring period to adequately evaluate performance in terms of sustainability.

At present, IAQ research is conducted largely within single disciplines, with little collaboration between specialised fields. As advocated by Sundell (2004, p.57), 'what is needed is a new multidisciplinary paradigm where generalized knowledge (putting findings in a total perspective) is as important as within-science knowledge.' There is a fundamental need for the translation of existing knowledge into practical, robust guidelines aimed at architectural and sustainability professionals. Through the involvement of the building design team, there is a considerable opportunity to accelerate the development of healthy, sustainable homes and establish innovative design strategies for exceptional IAQ.

As suggested by Yu & Kim (2011), there is a need for criteria on the certification of materials with regards to their potential impact on the quality of indoor air. This is supported by Bluyssen (2010), who suggests that existing sustainability labels do not provide sufficient information required to identify indoor sources of pollution which have the potential to affect occupants' quality of life. Furthermore, Levin (2012) explains problems with low-emitting materials certification, suggesting the invalidity and unreliability of tests through variations in test atmospheres, in humidities, sample representativeness and repeatability.

Minimum standards and legislation for IAQ are essential to ensure the quality of the indoor environment is not diminished through the drive for energy efficiency. This will require increased awareness of the interconnectivity of sustainability concepts and a promotion of the benefits of healthy housing design. In addition, an economical, practical and robust measurement strategy is required to ensure the feasibility of IAQ monitoring of the current UK building stock.

6. Conclusions

This paper emphasises the lack of attention to IAQ from current sustainable assessment methods through a comprehensive review of relevant criteria. For instance, BREEAM multi residential, BREEAM EcoHomes, BREEAM Domestic Refurbishment, the Code for Sustainable Homes, and the Passivhaus standard all ignore fundamental strategies for the protection of human health and wellbeing; such as radon prevention, pre-occupancy flush, moisture control, garage pollutant protection, combustion venting and indoor contaminant control. Furthermore, all assessment methods reviewed neglect the importance of providing information on IAQ to occupants through the building user guide. The significance of post occupancy evaluations, particularly the physical measurement of IAQ has also been disregarded.

Future research needs include the translation of existing knowledge from indoor sciences on IAQ to practical, relevant design guidelines aimed primarily at architectural and sustainable consultant professionals. In addition, further research is required to investigate the effectiveness of sustainability assessment methods including emission certifications in reducing occupant exposure to indoor air pollution. An economical IAQ measurement strategy will be paramount to ensure IAQ criteria are sufficiently represented in future domestic sustainability/energy codes.

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7. References

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