How loud is too loud?
Noise from domestic mechanical ventilation systems

Jack Harvie-Clark[*1], Nick Conlan[1], Weigang Wei[1], and Mark Siddall[2]

1 Apex Acoustics Ltd
William Street
Gateshead, UK
**jack.harvie-clark@apexacoustics.co.uk*

2 LEAP
3 Toll House Road
Durham, UK

ABSTRACT

Noise from domestic ventilation systems is currently a little understood problem in the UK. Other European countries that have a longer history of using mechanical domestic ventilation systems have introduced noise limits for these systems. Without mandatory limits for noise in UK, noise is not a factor that is often considered during the design. However, noise can be a significant constraint to the use of ventilation systems. Research is reviewed from across Europe and North America that indicates residents turn off ventilation equipment with objectionable noise. Without adequate ventilation in modern airtight dwellings, poor air quality can have a significantly adverse effect on the health of the occupants. There is a lack of evidence in the literature and performance standards for appropriate noise metrics and values that occupants find acceptable: this research is urgently required, and the steps to realise this are outlined. Causes of excessive noise are found to originate due to problems during the design, procurement, installation, commissioning and operation of ventilation systems.A suitable metric is required along with regulatory control to ensure that residents are not forced to choose between intolerable noise or inadequate air quality.

KEYWORDS

Noise,domestic,mechanical ventilation

1 INTRODUCTION

Noise can be a significant constraint to the use of domestic ventilation systems. Almost every study on domestic mechanical ventilation, in countries where there are problems with mechanical ventilation, refers to noise as a reason that the systems are not used as intended by the designers(REHVA, 2012; Sharpe et al, 2016;McGill et al, 2015;Brown &Gorgolewski, 2015;Balvers et al, 2012; Hady et al, 2008; Kurnitski et al, 2007). Someof these studies detail how occupants turn down their ventilation systems to a level of noise that is tolerable, or disable them entirely to prevent the perceived noise nuisance. In modern airtight dwellings, effective ventilation is vital to ensure adequate Indoor Air Quality (IAQ), and prevent adverse health effects of inadequate ventilation (Dimitroulopoulou, 2012). The noise problem in domestic ventilation is not ubiquitous – van der Pluijm (2010) notes that there are no reports of this problem from Germany and Sweden, for example. While the potential causes of excessive noise are documented (Harvie-Clark et al, 2014), the levels and character of noise that are unacceptable to residents are not well researched.

A complication when reviewing the literature is that there are other reasons that people also often cite for turning their ventilation systems off, such as to avoid the cost of electricity, or to avoid draughts (Sharpe et al, 2016), and therefore resident's reports may not always be candid. For example, McGill (McGill et al, 2015) reports:
… at the initial interview occupants stated that they did not have any problems with the system; however, during the building survey they mentioned they had turned the ventilation system off as it was making a loud noise.

A larger body of noise research focuses on annoyance in office environments, seeking to detail noise levels that interfere with task performance, linking to productivity and hence financial performance of staff (Leventhall, 1998; Ayr, 2002; Wang & Novak, 2010). Another body of evidence concerns the effects of noise on sleep (see Marquis-Favre et al, 2005 for a review), mainly focussing on the effects of environmental noise on people sleeping.There is a marked absence of study of noise tolerance of people to their own ventilation systems.

The situation for occupants is different to the effects of environmental noise; the period when people are getting to sleep may be the most critical. At this time background noise from both internal and external sources is likely to be lower than at other times, and the activity of falling asleep is one of inactivity and hence little self-generated noise. Under these conditions, noise from mechanical ventilation systems is likely to be more noticeable than at other times. Any particular source of noise that is noticeable has the potential to be annoying. This may be because of the perceived interference with the need for quiet, in the sense of freedom from interruption as well as low noise level, described by Andringa&Lanser (Andringa&Lanser, 2013). The context is also important: in a rural setting with little environmental noise, or in modern dwellings with well-sealed façade elements in a range of settings, the background noise may be low. In these circumstances, any noise from the mechanical ventilation may be more prominent than other sources, and therefore attract attention.

How can noise from domestic mechanical systems be assessed to capture the range of tolerances that different people may exhibit?The purpose of a suitable metric would be to ensure that only very few people – or possibly nobody – would be motivated to restrict the use of the ventilation system due to noise. The purpose of this paper is to explore these questions and identify research that is required where there are gaps in the literature.

2 NOISE MODELS AND METRICS

2.1 Noise response models

A simple response model to noise is illustrated by Leventhall(Leventhall, 1998), and identifies three stages, namely *detection, perception,* and *response*. Leventhall notes that:
the response is conditioned by parameters in addition to the physical attributes of the noise alone, including personal and situational elements…

Although Leventhall’s 1998 research concerns noise in offices, most of the concepts are relevant for residents responding to noise from domestic ventilation systems. He studies the spectrum balance, frequency composition, and fluctuations, which are features that are not currently used to consider noise from domestic ventilation systems in the UK. The Qaulaity Assessment Index(QAI) methodology described by ASHRAE does address spectrum balance, see below. Further investigations of fluctuating noise tolerance typically concern the effect of people in office environments, such as that by Wang and Novak (Wang and Novak,2010).

A more complex response model to indoor environmental conditions is discussed by Boerstra (Boerstra, 2016); central to this thesis is that control over the personal indoor environment can significantly affect the response to indoor climate conditions. This idea has been espoused by many people investigating conditions in offices, notably Leaman et al (Leaman et al,1999). It is not currently known whether people may be more tolerant of noise from domestic ventilation systems where they have control over the systems, where they perceive a benefit from operation of the system. Researchers’ comments suggest that the opposite may be true – that there is next to no tolerance of noise from these sources, especially as the level of knowledge of the purpose of ventilation is low (Baborska-Narozny & Stevenson, 2017),

(Brown & Gorgolewski, 2015)and there is little perceived benefit in their operation. According to Brown &Gorgolewski:
all 27% of respondents who had disabled their HRV did so because of its objectionable noise

2.2 Noise metrics

Noise metrics have been developed to correlate with human response to sound in many different contexts. It is worth remembering that sensitivity to different frequencies of sound varies with sound level, as illustrated by the equal loudness contours of ISO 226. This means that one fixed set of frequency weightings may be a good indicator of loudness at one sound level, but at different sound levels it will not.A large number of noise metrics are reviewed by Marquis-Favre et al (Marquis-Favre et al,2005). Factors affecting noise annoyance are considered, along with the noise source, characteristics of the sound and non-acoustic factors.

Pearsons& Bennett (Pearsons& Bennett,1974) classify noise metrics into categories including speechinterference and annoyance. Although this publication pre-dates many more recent metrics, it illustrates the point that the metrics designed to describe building services noise levels are categorised for speech interference, rather than annoyance. Even though the concept for comfortable noise in offices may be considered in terms of effect on productivity, this is very different from relaxing in one’s home, or falling asleep.

The A-weighted scale is widely acknowledged to under-represent the loudness of sounds with a strong low frequency content. For example, the WHO Community Noise Guidelines(Berglund et al, 1999) indicates that:
Where noise is continuous, the equivalent sound pressure level should not exceed 30 dBA indoors, if negative effects on sleep are to be avoided. When the noise is composed of a large proportion of low-frequency sounds a still lower guideline value is recommended, because low-frequency noise (e.g. from ventilation systems) can disturb rest and sleep even at low sound pressure levels.

The A-weighted sound level has become the default metric to indicate noise levels in many scenarios; it is often tested and found to be the indicator that correlates best with perception of noise levels (e.g. Ayr, 2003) in particular circumstances.

3 NATIONAL STANDARDS AND EXPERIENCE

A systematic review of national guidelines for noise from mechanical services in a domestic setting has not been carried out, although some of the references below have undertaken this in some parts of the world.

3.1 UK

In the UK, noise from domestic building services is not currently regulated. There is guidance in the standards for ventilation (Approved Document F, 2010) that noise from continuously running systems should not exceed 30 dB(A) in living rooms and bedrooms, with a reference to a previous version of BS 8233 (BSI, 1999). It appears that the 30 dB(A) value is simply taken from environmental noise studies as the threshold above which adverse effects of noise on sleep become apparent – ie the LOAEL (Lowest Observable Adverse Effect Level), rather than correlated with occupant response to ventilation systems.

The Chartered Institute of Building Services Engineers (CIBSE, 2015) offers three metrics for mechanical services noise limits in its Guide A: Environmental design. These are NR 25, 30 dB(A), and 55 dB(C) for bedrooms. The authors have indicated that the dB(C) values are based on experience with sound level meters prior to the modern day, when real time analysers can log in frequency bands and overall weighted values simultaneously. The C-weighted limit is intended to highlight excessive low-frequency noise.

The effectiveness of ventilation systems in the UK has been investigated by the Zero Carbon Hub (ZCH, 2016), which found that:
In summary, the Hub team found things going wrong at multiple stages of the construction process at every site… At 5 of the 6 sites, fans were operating at only half the required duty or lower, i.e. flow rates were far too low. The end result was that nearly all of the 13 occupants interviewed by the team across the sites had turned off their ventilation systems, finding them too noisy, especially at night.

Failings in the design, specification, procurement, installation, commissioning and maintenance are detailed in the ZCH report.The National House Building Council (NHBC) introduced its Chapter 8.3 “Mechanical Ventilation with heat recovery” into its Standards 2014, in response to observations of poor practice. In April 2017 the NHBC produced a review of compliance with its own standards. The Technical Extra report (NHBC, 2017) follows investigations at over 200 sites, looking at six key areas of design and drawings, installation, ducting, air transfer, testing and commissioning, and handover to the homeowner. The report details significant findings of non-compliance, repeating many of the findings of the ZCH report, and reminds readers of what compliant practice would look like.

McGill et al (2015) list common MVHR shortcomings, and include noise as a problem. Baborska-Narozny&Stevenson (Baborska-Narozny&Stevenson,2016) evaluate 40 low carbon homes, and finding that noise is frequently a problem for occupants, with 30% of occupants switching fans off due to the noise.

3.2 Sweden

Sweden has a well-established acoustic classification system, documented in Swedish Standard SS 25267 (Svensk Standard 2015). This has four Classes for noise from mechanical ventilation, reproduced in Table 1.

Table 1: Class limits under the Swedish Classification system

Type of space and source	Class / L_{eq} ,dB(A)			
	A	**B**	**C**	**D**
In spaces for sleep, rest or everyday social contact	≤ 22	≤ 26	*	≤ 30

Requirements for sound class C are described in National Board of Building, Planning and Housing building regulations BBR Section 7:21, and therefore omitted from the classification system. Reports from the authors of the standard indicate that:
For sound class B the experience is massive in Sweden, and for sound class A it's a clear consensus that the values are adequate.

3.3 Finland

A Finnish study by Kurnitski (Kurnitski,2007) describes measurements of not just ventilation performance, but also of measured noise levels, in 102 homes. This study is unique, as noted in Existing Buildings, Building Codes, Ventilation Standards and Ventilation in Europe:
The Final Report (REHVA, 2012) that it is the only study that documents the noise levels and also compares the occupant-controlled point of operation with the noise levels. The study found a dependency between the maximum noise level in bedrooms and ventilation noise complaints. An upper limit threshold of 22 dB(A) resulted in < 10 % complaints and an upper limit threshold of 25 dB(A) resulted in < 20 % complaints. A significant dependency was

found between the maximum fan speed of the ventilation unit and complaints, rather than the whole dwelling ventilation rate. This study was one of the first to note that people operated their ventilation systems at the level at which they could tolerate the noise, rather than at the level that provided the minimum suggested ventilation rates. This finding is repeated in many other subsequent studies.

3.4 Netherlands

The experience of the Netherlands appears to be similar to that subsequently experienced in the UK. Problems with mechanical ventilation systems have been noted and adverse media coverage has resulted for modern air-tight homes. Hady et al (Hady et al, 2008) report on the characteristics and associated adverse health effects in under-ventilated homes, reporting noise and draughts being the biggest causes for dissatisfaction. Noise is reported as a barrier for occupants' use at the ventilation set point.

Balvers et al (Balvers et al,2012) investigated 299 homes, and notes that:

Noise annoyance results in occupants setting the system in a low setting or turning it completely off, leading to insufficient ventilation… The most common shortcomings related to high noise levels(where >30% of the homes did not comply with the reference level) ... Noise levels are higherthan 30 dB(A) in one or more bedrooms in 86% of homeswith MVHR in the setting in which the ventilation system isproviding a sufficient ventilation rate.

3.5 Europe

A pan-European acoustic collaboration, COST Action TU-0901, concluded in 2014 (Rasmussen, 2014). Although focussed on producing a classification system for sound insulation, noise from building services was included; the Classes for noise from building services are shown in Table 2. There is a reference to ISO 16023 for the measurement of sound levels.

Table 2: Class limits for service equipment noise proposed in COST Action 0901

Type of space and source	Class / L_{eq} ,dB(A), and dissatisfaction, %					
	A	**B**	**C**	**D**	**E**	**F**
Rooms in dwellings; ventilation / heating installation	≤ 20	≤ 24	≤ 28	≤ 32	≤ 36	≤ 40
Guide to occupant dissatisfaction, %	≤ 5 %	≈ 5 %	≈ 10 %	≈ 20 %	≈ 35 %	≥50 %

This does not distinguish between different room types, and has much lower limits for the highest performance, Class A than may be anticipated by designers in the UK. The information about Classes suggests occupant dissatisfaction levels as shown in Table 2 with around 20 % dissatisfaction for noise levels not exceeding 32 dB(A).

Taken from a ventilation rather than acoustic point of view, REHVA (REHVA,2012) notes, in reviewing noise guideline levels across Europe, that:

Many of the noise limit levels seem quite high, which is especially the case for bedrooms. A common European regulation is required. It should define noise levels in only one type of units to avoid confusion.

Andfurther comments that echo those made by many other investigators:

The reviewed studies show that ventilation rates, indoor environmental parameters and noise do not comply with regulations. Deviations between measured and required values areconsiderable and actions need to be taken. A new European guideline is needed, which would serve as a base document for legislators in EU countries or in the European Commission. The guideline should provide guidance on suitable design, construction, *maintenance andinspections of ventilation systems. For improved efficiency, the inspection of ventilation systems should be merged with the inspection of air-conditioning systems and energy auditing. More effort should be put into education of all parties involved in design, construction and operation of ventilation systems.*

Furthermore, in dwellings:

Noise in mechanical ventilation systems is a common problem. Even though systems are often able to provide the required ventilation rate, the occupants lower fan speed setting because of the noise disturbance. Too little attention is paid to noise during the design and construction phases. Surveys report that almost all regulated noise levels are too high in practice.

3.6 USA

A large body of work has been undertaken by ASHRAE to determine the acceptability of noise levels. The 2015 ASHRAE Fundamentals Handbook (ASHRAE, 2015) includes a detailed discussion of a range of parameters for assessing noise from building services.The preferred criterion identified is the RC Mk II, which includes the Quality Assessment Index (QAI) proposed by Blazier (Blazier, 1995, 1997). The QAI is a measure of the spectral imbalance of sound levels, and it is claimed that more imbalanced sounds lead to greater dissatisfaction and complaints. Excessive high-frequency sound is described as a "hiss", mid-frequency excess as "roar", and low frequency excess a "rumble". Interestingly, the ASHRAE Handbook indicates that a level of NC / RC 30 for "Living areas", and indicates "Approximate Overall Sound Pressure Levels of 35 dB(A) and 60 dB(C). These values are conspicuously 5 dB higher than the WHO Guidelines (WHO, 1999), and the Handbook comments:

It is recommended that when specifying background sound levels in dBA, the dBC is also included in the specification and does not exceed the dBA reading by more than 20 dB.

It is speculated that a possible reason for the higher permissible sound levels from mechanical services is due to the greater cultural acceptance of this type of noise, with mechanical services having greater penetration in North America.

When investigating inhabitants use of ventilation in Toronto (Brown & Gorgolewski, 2015), the researchers reported the QAI values but not the overall sound pressure levels. They noted that:

… QAI values were high and where the noise caused by continuously running bathroom fans prompted 27% of respondents to disable their fan…

Thus the actions of the inhabitants are attributed to the quality of the sound rather than the overall level. This study is unique in the literature reviewed to conclude that the sound quality is unacceptable, rather than the sound level. The fact that this is due to noise in the bathroom rather than bedroom or living room is also significant.

4 OTHER SOURCES OF INFORMATION

4.1 Sleep in hotels

A fundamental purpose of a hotel is to provide a place to go to sleep. Some hotels place more emphasis on the acoustic performance of their brands than others, even making it a unique selling point. It is interesting to compare the range of noise levels that hoteliers provide in their brand standards when new developments are constructed. Some well-known four-star global hotel brands adopt a standard of NR 30 in guestrooms for mechanical services noise, which typically equates to noise levels in the range 33 – 36 dB(A). Comparison with the values in in Table 2 would suggest that a high proportion of people may well be dissatisfied with noise levels as high as these.

Conversely, a large value-range UK hotel chain that places great emphasis on acoustics has a limit of NR 20 for noise from the mechanical ventilation heat recovery system – which are

installed in a per-room arrangement. The hotel chain has a money-back guarantee if residents do not have a good night's sleep; the performance specification for new developments continually evolves in response to complaints received. This represents an effective quality system for meeting residents' expectations for noise, amongst other factors. Typical installed noise levels have been measured by the authors between NR 18 – 20, equating to 22 – 24 dB(A). It may be considered that these values represent noise levels at which people do not feel they have any valid cause for complaint, as there is a financial incentive to do so.
It is also interesting to consider that comfort cooling systems in hotels almost always operate at noise levels that are unlikely to be compatible with undisturbed sleep; they are likely to only be used during the sleeping period if the need for thermal comfort is considered to be greater than the need for acoustic comfort, such that occupants may accept elevated noise levels over which they have control. There appears to be a general cultural acceptance that this is the case; clearly it need not be so from an engineering perspective, but it is cheaper for hotel developers to permit higher noise levels from comfort cooling systems.

4.2 Passivhaus standards

The Passivhaus standard for noise from the ventilation system is ≤ 25 dB(A). The authors have not been able to determine how this value was determined, and are not aware of any noise complaintsfrom ventilation system in Passivhauses in the UK.

5 SOURCES OF NOISE FROM DOMESTIC VENTILATION SYSTEMS

Excessive noise from domestic ventilation is typically symptomatic of other problems, and highlights one or more failings in the design, specification, procurement, installation or operation of mechanical ventilation systems. The knowledge and experience to mitigate noise from mechanical ventilation systems is well established, but is rarely employed in the residential construction sector in the UK.

There are many different typologies for the implementation of domestic ventilation. In some countries, such as Sweden, in blocks of flats it is common to have a centralised ventilation system. In the UK, each dwelling usually has its own ventilation system; the choice of system is usually determined by speculative housebuilding companies on the basis of thermal performance requirements. Particular sources of noise are likely to be dependent on local building customs and ventilation systems adopted.

Problems that can lead to excessive noise are presented by Harvie-Clark et al (Harvie-Clark et al, 2014), for example. Typical problems and the actions to avoid them in the UK are well documented by NHBC (NHBC, 2017), Zero Carbon Hub (ZCH, 2016), McGill et al (McGill et al, 2015), Dengel&Swainson (Dengel&Swainson, 2013), amongst others. Some studies note that ventilation systems are frequently commissioned "by ear", rather than by flow measurement e.g. (ZCH, 2016). While this practice acknowledges the importance of the noise from these systems, it does nothing to ensure that sufficient ventilation is also provided.

6 FUTURE WORK REQUIRED

The content in this section was developed at the HEMAC workshop (HEMAC, 2017). The future work required may be broken down into several categories. Most importantly, the question of what noise characteristics are best suited for ventilation systems for sleep and for relaxation should be addressed. Guidance is required for stakeholders to illustrate this, and government policy should be informed by the results. This may be achieved through the following research objectives:

i.. Identify acoustic triggers and mitigating action by occupants on their MV systems
ii. Diagnose problem noise sources and characteristics

iii. Determine the ranges of ventilation system noise characteristics best-suited for bedrooms for sleep, living rooms, and bathrooms.
iv. Inform policy and practice through guidance

It is suggested that these objectives may be achieved through the following actions:

Table 3: Potential work packages to determine sound levels that avoid causing occupants to curtail ventilation

Workpackage	WP overview
1	Occupant perception survey of installed systems, including measurements of the noise levels and recording of noise signal for laboratory studies.
2	Larger-scale survey of as-built mechanical ventilation noise levels, to characterise the potential extent of the problem when correlated with data from occupant perception survey and lab tests.
3	Physical survey of problem sources and resultant noise characteristics: design, installation, operation and maintenance.
4	Laboratory study of subjective testing and optimisation of MV noise characteristics for sleep, and for relaxation, using measured source data.
5	Mapping pathways to impact - implications for policy and practice

As with other aspects of new-build dwellings, the author’s experience is that many contractors in the UK seek to minimise costs by simply providing the minimum requirements of the regulations. Where noise levels remain unregulated, there is little incentive to take appropriate steps during the design, specification, procurement, installation and commissioning to ensure that suitable levels are achieved.

7 CONCLUSIONS

Many residents in parts of Europe and beyond are dissatisfied with their ventilation systems due to the noise. This dissatisfaction causes them to reduce or disable entirely the operation of those ventilation systems. This represents a potential health hazard in modern air-tight homes, as infiltration cannot be relied upon to achieve adequate IAQ. Excessive noise levels and unacceptable quality of noise are separately reported as issues leading to interference with ventilation systems.

The particular characteristics of ventilation system noise that cause occupants to interfere with the operation of their systems are not well researched; there is little evidence in the literature about people’s tolerance to noise from their own ventilation systems. Research is urgently needed to identify a suitable metric for ventilation system noise, and determine appropriate guideline values for different rooms.The Swedish and COST Action TU 0901 classification schemes emphasise the value of noise levels well below 30 dB(A).

In the interim, the highest limit that could be proposed for mechanical services noise in bedrooms is 30 dB(A), to avoid adverse effects on sleep. Where there is anticipated to be significant external noise ingress, a lower limit should be proposed such that the combined internal level does not exceed 30 dB(A). The literature suggests that a more prudent limit for mechanical services around 24 - 26 dB(A) is unlikely to cause an adverse reaction from most occupants while falling asleep, noting that 20 % of Finnish respondents found this too noisy. This may be an unnecessarily onerous target, depending on the characteristics of the noise.There is insufficient evidence to propose limits in living spaces and bathrooms without suitable research.

In the absence of this work there is an ongoing risk that noise will continue to be cited as a reason that people chose to curtail the operation of their mechanical ventilation systems, and suffer the effects of poor IAQ as a result. People should not be forced to choose between intolerable noise or poor IAQ in their homes.

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9 REFERENCES

Andringa, T. C., & Lanser, J. J. (2013). How Pleasant Sounds Promote and Annoying Sounds Impede Health: A Cognitive Approach. *Int. J. Environ. Res. Public Health, 10*(4), 1439-1461. doi:doi:10.3390/ijerph10041439

ASHRAE. (2015). *2015 ASHRAE Handbook Heating, Ventilating, and Air-Conditioning Applications. SI Edition.*

Ayr, U., Cirillo, E., & Martellotta, F. (2002). Further investigations of a new parameter to assess noise annoyance in air-conditioned buildings. *Energy and Buildings*, 765-774.

Ayr, U., Cirillo, E., Fato, I., & Martellotta, F. (2003). A new approach to assessing the performance of noise indices in buildings. *Applied Acoustics, 64*, 129-145.

Baborska-Narozny, M., & Stevenson, F. (2017). Mechanical ventilation in housing: understanding in-use issues. *Proceedings Institute of Civil Engineers - Engineering Sustainability, 170*, pp. 33-46. doi:doi.org/10.1680/jensu.15.00053

Balvers, J., Bogers, R., Jongeneel, R., van Kamp, I., Boerstra, A., & van Dijken, F. (2012). Mechanical ventilation in recently built Dutch homes: technical shortcomings, possibilities for improvement, perceived indoor environment and health effects. *Architectural Science Review*, 4-14. doi:dx.doi.org/10.1080/00038628.2011.641736

Blazier, W. E. (1995). Sound quality considerations in rating noise from heating, ventilating, and air-conditioning(HVAC) systems in buildings. *Noise Control Engineering Journal*, 53-63.

Blazier, W. E. (1997). RC Mark II: A refined procedure for rating the noise of heating, ventilating, and air-conditioning (HVAC) systems in buildings. *Noise Control Engineering*, 243-250.

Boerstra, A. C. (2016). *Personal control over indoor climate in offices : impact on comfort, health and productivity.* Eindhoven, Netherlands: Technische Universiteit Eindhoven. Retrieved from http://repository.tue.nl/079d4ef4-04d3-4789-8101-8f0fdd7ca3a5

Brown, C., & Gorgolewski, M. (2015). Understanding the role of inhabitants in. *Building Research & Information, 43*(2), 210-221. doi:dx.doi.org/10.1080/09613218.2015.963350

BSI. (2014). *BS 8233:1999, Sound insulation and noise reduction for buildings. Code of practice.*

CIBSE. (2015). *CIBSE Guide A: Environmental Design.* Chartered Institute of Building Services Engineers.

Crowe, K. (1974). *A History of the Original Peoples of Northern Canada.* Montreal: McGill/Queen's University Press for the Arctic Insitute of North America.

Dengel, A., & Swainson, M. (2013). *Assessment of MVHR Systems and air quality in zero carbon homes.* NHBC Foundation Research.

Dimitroulopoulou, C. (2012). Ventilation in European dwellings: A review. *Building and Environment*, 109-125.

Hady, M., van Ginkel, J., Hasselaar, E., & Schrijvers, G. (2008). The relationship between health complaints, the quality of indoor air and housing characteristics. *Indoor Air*.

Harvie-Clark, J., Siddall, M. J., & Hunter, D. (2014). Noise from domestic ventilation systems. *Institute of Acoustics Conference Proceedings.* IOA. Retrieved from www.apexacoustics.co.uk/wp-content/uploads/2015/07/Apex-Acoustics-MVHR-design-poster.pdf

HEMAC Sandpit. (2017, April 25). Health Effects of Modern Airtight Construction. *Noise effects*. (J. Harvie-Clark, D. Waddington, J. Laverge, M. Marinho, R. Gupta, R. Menon, & W. Swan, Eds.) Glasgow. Retrieved from https://hemacnetwork.com/sandpit/

Kurnitski, J., Eskola, L., Palonen, J., & Seppänen, O. (2007). Use of mechanical ventilation in Finnish houses. *European BlowerDoor Symposium*.

Leaman, A., & Bordass, B. (1999). Productivity in buildings: the ‘killer’ variables. *Building Research & Information, 27*(1). doi:dx.doi.org/10.1080/096132199369615

Leventhall, H. G., & Wise, S. S. (1998). Making noise comfortable for people. *ASHRAE Transactions, 104*.

Marquis-Favre, C., Premat, E., Aubree, D., & Vallet, M. (2005). Noise and its Effects – A Review on Qualitative Aspects of Sound. Part I: Notions and Acoustic Ratings. *Acta Acustica United with Acustica, 91*, 613-625.

McGill, G., Oyedele, L., & Keeffe, G. (2015). Indoor air-quality investigation in code for sustainable homes and passivhaus dwellings: A case study. *World Journal of Science, 12*(1), 39-60. doi:10.1108/WJSTSD-08-2014-0021

NHBC. (2017). *NHBC Technical Extra Issue 22.* NHBC. Retrieved from www.nhbc.co.uk/NHBCpublications/LiteratureLibrary/Technical/TechnicalExtra/filedownload,71937,en.pdf

Pearsons, K. S., & Bennett, R. L. (1974). *Handbook Of Noise Ratings.* National Aeronautics And Space Administration. Retrieved from https://archive.org/stream/nasa_techdoc_19740015162/19740015162_djvu.txt

Rasmussen, B., & Machimbarrena, M. (2014). *Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions.* COST Action TU0901.

REHVA. (2012). *Work Package 5: Existing Buildings, Building Codes, Ventilation Standards and Ventilation in Europe.* Healthvent: Health-Based Ventilation Guidelines for Europe.

Sharpe, T., McGill, G., Gupta, R., Gregg, M., & Mawditt, I. (2016). Characteristics and performance of MVHR systems: a meta study of MVHR systems used in the Innovate UK Building Performance Evaluation Programme.

Svensk Standard. (2015). *Svensk Standard SS 25267:2015, Acoustics – Sound classification of spaces in buildings – Dwellings.*

Van der Pluijm, W. M. (2010). *The robustness and effectiveness of mechanical ventilation in airtight dwellings. A study to the residential application of mechanical ventilation with heat recovery in the Netherlands.* Eindhoven, Netherlands: Eindhoven University of Technology.

Wang, L. M., & Novak, C. C. (2010). Human performance and perception-based evaluations of indoor noise criteria for rating mechanical system noise with time-varying fluctuations. *ASHRAE Transactions, 116*(2). Retrieved from http://digitalcommons.unl.edu/archengfacpub/41/?utm_source=digitalcommons.unl.edu%2Farchengfacpub%2F41&utm_medium=PDF&utm_campaign=PDFCoverPages

ZCH. (2016). Retrieved from www.zerocarbonhub.org: www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH_Ventilation.pdf