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Article

A Natural Ventilation Alternative to the Passivhaus Standard for a Mild Maritime Climate

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Abstract: This study examines the need in mild maritime climates, such as the southern areas of the UK, for mechanical ventilation with heat recovery (MVHR) as required by the German Passivhaus standard. It considers the comfort, air quality and energy impacts of MVHR *versus* natural ventilation and reviews the post-occupancy monitoring data of two flats in Cardiff designed to Passivhaus standards, one of which had been operated as a naturally ventilated building rather than with MVHR. The energy consumption of this free-running flat was significantly lower (36 kWh primary energy/m²a) than the Passivhaus Planning Package modeling had predicted (93 kWh primary energy/m²a) with no adverse effects on occupant comfort, air quality or excessive humidity, and advantages of lower capital cost and maintenance. The paper concludes that in climates with mild winters and cool summers the use of MVHR could be omitted without compromising comfort levels and achieving at least equivalent energy savings resulting from adopting the Passivhaus model and at a lower capital cost. This suggests the potential for a naturally ventilated, ultra-low energy model with lower capital investment requirements and lower disruption when applied to retrofit that would facilitate its mainstream adoption.

Keywords: passivhaus; mechanical ventilation with heat recovery; natural ventilation; energy efficiency; sustainability; thermal comfort; air quality; zero carbon buildings; energy modeling; energy retrofit

1. Introduction

The UK government's target for the construction of zero carbon emissions buildings by 2016 [1] has driven the industry to examine existing successful models and standards for very low energy housing to be found internationally. The German Passivhaus standard is one of these models and its adoption in the UK is gaining momentum, with courses training designers to be "Certified Passivhaus Designers" being run at Strathclyde University and the Building Research Establishment. The Passivhaus standard is considered a well defined and rigorous standard, and it has been successfully adopted in the construction of over 40,000 buildings worldwide to date [2], an increasing number of which have undergone post occupancy assessments to confirm the expected energy savings [3]. Its fundamental characteristic of minimizing heating requirements results in buildings with significantly reduced carbon emissions compared to the current average buildings and could contribute towards achieving the UK government goal of an 80% reduction in carbon dioxide (CO_2) emissions by 2050 from 1990 levels [4].

Despite the potential for the Code for Sustainable Homes to provide a framework to achieve the zero emissions target, the Passivhaus is gaining popularity not only due to its proven track record in achieving up to 90% reduction in heating energy in Germany compared to the existing stock and 75% reduction compared to current standards [5] but also due to its simplicity. While the Code for Sustainable Homes is a more comprehensive environmental standard that addresses the use of all resources as well as ecology, pollution, health and building management [6], its system of assessment is necessarily complex and it is precisely its complexity that makes its adoption challenging. The Passivhaus standard's absolute targets of 15 kWh/m²a heating and 120 kWh/m²a primary energy are clear and the design guidance and software are educational as well as useful tools to implement the standard's targets. With the aim of making the standard applicable more widely and in particular to warmer climates, taking into account the original standard was developed for the cold continental European climate, a review of the Passivhaus standard was undertaken as part of the Passive-on program. The review suggested the inclusion of a limit of 15 kWh/m²a for useful, sensible energy demand for space cooling in addition to the 15 kWh/m²a for heating, and a lower airtightness requirement of 1 ach (air changes per hour) at 50 Pa in climates where ambient temperature does not drop below 0 °C. No change to the overall primary energy limit of 120 kWh/m²a was suggested nor to the key approaches of high fabric insulation and mechanical ventilation with heat recovery [7]. However, the current certificate for a "Certified Passivhaus" does include the 15 kWh/m²a for space cooling but still maintains the requirement for an airtightness of 0.6 ach at 50 Pa [8].

This essentially wholesale adoption of the standard within a warmer context, which differs from the one it was developed for, should be and is being questioned [9]. In particular, the adoption of MVHR in the UK mild maritime climate, which is significantly different from the central European continental climate, is thought to potentially use more energy than it saves [10]. Furthermore, MVHR is associated with additional capital and maintenance costs and is thought to have potential health implications if the maintenance is neglected [11] and often requires a change in user habits.

This paper discusses the adoption of the Passivhaus principles and in particular the use of MVHR as a means of creating low carbon buildings in the mild maritime climate of southern UK and the alternative of natural ventilation. The study reviews issues of comfort, air quality and energy consumption. It also reports on a post-occupancy monitoring of over two years of occupation of a case study building completed in 2008, comprising two flats designed to the Passivhaus standard and located in Cardiff, Wales. The Passivhaus Planning Package (PHPP 2004) is used to test the impact of varying design and construction parameters as well as building location on the energy consumption of a case study building.

Of relevance to the debate is that the MVHR in one of the two flats was never switched on by the occupant and the resulting energy consumption (primary energy 36 kWh/m²a) proved to be significantly lower than that modeled with the Passivhaus Planning Package (primary energy 93 kWh/m²a). While one case study does not provide statistical evidence, it could suggest that if buildings are appropriately designed the MVHR can be dispensed with, while still maintaining a high energy performance and comfort levels and minimizing capital and maintenance costs.

2. The Passivhaus Standard

The Passivhaus standard was developed in Germany in the 1980s by Dr. Bo Adamson and Dr. Wolfgang Feist, who aimed to achieve an economically viable option for a minimal energy dwelling that is also comfortable. By reducing the heating load to less than 10 W/m², a conventional heating system could be omitted [12] thus saving capital that could be used for increasing the fabric insulation. The requirements for the standards include the following:

- An annual space heating requirement that is less than 15 kWh/m² or a heating load of less than 10 W/m²;
- An annual cooling requirement including dehumidification that is less than 15 kWh/m² or a cooling load of less than 10 W/m², a temporary figure for the dehumidification is added that will be confirmed in due course;
- Total primary energy consumption may not exceed 120 kWh/m²a for heat, hot water and household electricity;
- And airtightness of 0.6 ach should not be exceeded.

These requirements are mainly performance-based, that is any method can theoretically be adopted to achieve the desired outcome. The exception is the requirement for airtightness, which is a method to achieve an energy efficient building envelope rather than intrinsically desirable goal. The design recommendations of the standard, which include recommendations for U-values, orientation and other traditional passive design principles, are not unique to the standard and are shared by various other models, such as the Minergy standard [13], and also various building prototypes such as the Rocky Mountain Institute building in Colorado [14]. The achievement of the Passivhaus standard was to combine well-understood principles in a clear and economic model.

It is worth reiterating that the ultimate goal of the standard and the design of any low carbon building is to achieve the lowest possible carbon emission building while maintaining a comfortable and healthy environment at an affordable cost. Standards are tools to achieve specific goals not ends to themselves.

Keeping these aims in mind, the use of MVHR is the recommended method in the Passivhaus model of providing the required ventilation and maintaining a comfortable and healthy environment at minimal energy costs. It is only one possible solution to providing ventilation. In order to assess alternative approaches to providing a ventilated, comfortable and healthy indoor environment the following key issues have to be considered.

- What is acceptable thermal comfort?

- What is a healthy and comfortable environment in respect of indoor air quality?
- What energy savings can be achieved with a MVHR?

3. Acceptable Thermal Comfort

The Passivhaus standard suggests assuming an internal temperature of 21 °C and to a certain degree the use of MVHR evens out the temperatures of different rooms providing uniform temperatures throughout the building. Variations in the temperature may be expected if the auxiliary heating system is localized such as with a wood stove. Only minimal variations can be expected where a heating coil is included in the supply air of the MVHR. Two aspects are to be questioned. The first is the set temperature of 21 °C and the second the uniformity of the temperature throughout the building.

A temperature of 21 °C does not always provide the most comfortable environment. Research into thermal comfort supports the view that occupants of free-running buildings experience a comfort band, which relates to external temperatures and is wider than that experienced in mechanically ventilated buildings [15–20]. Field studies by Humphreys and Nicol [19] showed a linear relation between indoor temperatures and comfort temperature, whereby the latter varied from around 17 °C to 32 °C and changed through the year as external temperatures changed. Furthermore, Humphrey (discussed in [19]) showed a linear relation in free-running buildings between the external temperature and the internal comfort temperature while the relation in conditioned buildings was more complex and non linear. In particular, in free-running buildings the comfort temperature rose in a linear fashion from approximately 17 °C where the external temperature was approximately 13 °C to a comfort temperature of approximately 29 °C where the external temperature was approximately 32 °C. The impact of the external temperatures on perceived comfort has to some degree also been incorporated in design standards such as the ASHRAE Standard 55 [21], which differentiates between winter and summer settings.

Furthermore, highly insulated buildings typically have a building fabric with a warmer surface temperature than poorly insulated buildings. This reduces the radiant cooling effect experienced in less insulted buildings. Taking into account that radiant heat losses can make up 45% of the body heat exchanged with the environment, lower air temperature can feel comfortable in such environments [22,23].

It is also understood that comfort depends on the perceived and actual ability to adapt oneself and the environment to become more comfortable [16]. Baker and Standeven [15] identify how the ability to open windows, draw a blind, use a fan as well as change their clothing increases the level of comfort. Baker [24] further identified that even if the alterations to make a space more comfortable are not implemented, the fact that they could be implemented increases the tolerance to the environment. Humphreys and Nicol [19] suggest where the ability to adapt does not exist, such as in conditioned buildings, the comfort band may be as narrow as ±2 °C, and as the ability to adapt increases so does the comfort zone. Brager and de Dear [17] go further to suggest that a variety of temperatures is in fact preferred by the occupants.

This research suggests that highly insulated and reasonably airtight but naturally ventilated buildings where occupants are in control of their environment and are able to make adjustments to maintain comfort would not need to achieve a fixed temperature of 21 °C to feel comfortable and occupants could tolerate lower and higher temperatures.

A uniform temperature in all rooms is also arguably not desirable [18,25]. Heschong's book Thermal Delight in Architecture [25] describes the variations in temperature within buildings as enriching the building experience. The CIBSE Guide B1 Heating [26] recommends higher temperatures in living areas and lower in sleeping areas. In particular the recommended temperatures are as follows:

- Bathrooms 26–27 °C;
- Bedrooms 17–19 °C;
- Hall stairs landing 19–24 °C;
- Kitchen 17–19 °C;
- Living rooms 20–23 °C;
- Toilets 19–21 °C.

The CIBSE range of temperatures suggests the potential for up to six degrees difference between the main rooms. Temperature variations between rooms can therefore not be considered detrimental to comfort.

4. Healthy and Comfort in Relation to Indoor Air Quality

The indoor air quality of a building is affected by the outdoor air quality, the sources of indoor air pollution and the ventilation rates. Assuming adequate outdoor air quality, the more fresh air is brought into a building, the more the pollutants are diluted and the better the indoor air quality. However high air exchange rates during the heating season are associated with increased heating energy costs and MVHR is one way to provide the required fresh air while reducing energy wastage [12].

Indoor air pollutants include pollutants from combustion, emissions from building materials, household equipment and consumer products as well as microbial sources such as bacteria, fungi, and molds growing indoors [27]. Dimitroulopoulou's [28] review of ventilation in European dwellings, states that while ventilation is used to dilute the pollutants a more effective way of ensuring good indoor air quality is to eliminate the sources of indoor air pollution. This view is also supported by the Passivhaus Institute [12] and the WHO [27].

WHO guidelines for indoor air quality [29] discusses the pollutants identified as health hazards. Of these, the pollutants relevant to non-industrial buildings include pollutants from external sources such as radon, nitrogen oxide and benzene, emissions from the burning of organic substances including tobacco (polycyclic aromatic hydrocarbons, carbon monoxide), emissions from building materials and furniture (benzene formaldehyde) and emissions from cleaning materials and consumer products (formaldehyde, benzene, Trichloroethylene, naphthalene (mainly from naphthalene-containing mothballs) and Tetrachloroethylene from dry cleaning).

Carbon dioxide is often measured and discussed in relation to indoor air quality. Carbon dioxide, which is emitted by occupants and normally found in concentrations of 300–2500 ppm in buildings, is harmless at these levels [30] and not considered by the WHO as needing to be controlled [27], and therefore is not included in the WHO guidelines [29]. Only when carbon dioxide levels reach 3% to 4% (*i.e.*, 30,000 ppm, 100 time higher than typical outside levels) does cellular acidosis take place, which is a non-toxic or damaging process that can be tolerate for limited periods of time and is reversible [31]. The focus on carbon dioxide, when assessing indoor air quality, is not due to its impact on health but rather because carbon dioxide is used as a surrogate for other indoor pollutants [32]. However, a study by Newell and Newell [33] monitoring carbon dioxide and volatile organic compounds (VOCs) in parallel showed that the levels of carbon dioxide are not necessarily representative of the VOC levels and therefore the levels of indoor emissions potentially hazardous to health. This suggests that judging the air quality by measuring carbon dioxide levels may be misleading and limited, and that buildings that have eliminated sources of VOCs can have elevated carbon dioxide levels and still provide healthy environments.

It is feasible to avoid sources of indoor air pollution and increasingly done. In particular, timber boards, including chipboard, MDF, OSB and ply, can contain formaldehyde resins and together with fabric finishing materials are the key source of formaldehyde in buildings [34], and zero or low formaldehyde replacements for these products exist. Highly insulated buildings may be able to avoid burning fuel inside the building for cooking and heating by using other energy efficient electrical means. Careful building specification can therefore contribute to reducing indoor air pollutants sources.

Secondly, the behavior of the occupants can affect the sources of pollutants [27]. The selection of cleaning products, the use of naphthalene-containing mothballs and dry cleaning facilities, as well as personal habits such as tobacco smoking can impact on indoor air quality and according to Newell and Newell [33] this impact can be more significant than the impact of building materials.

Recognizing when the indoor air quality is deteriorating does not necessarily require specialist equipment and as suggested by Engvall *et al.* [35] occupants may perceive the space to be stuffy or unpleasantly smelling when pollutant levels are elevated but still relatively low and at healthy levels. Engvall *et al.* [35] compared the air quality in a number of flats with different air change rates and found no physical or building-related disadvantage to lower ach rates but did find a lower comfort level was experienced by the 44 subjects. This could suggest that a carefully designed building with minimal internal sources of pollutants could be operated to provide sufficient fresh air by allowing the occupants to open and close vents and windows when they perceive the air quality to be inadequate and they would most likely introduce fresh air before the level of pollutants reach levels that might affect the health of the occupants.

The humidity in the environment can have an indirect impact on the air quality by enabling the growth of fungi, molds and dust mites. When cold damp air is brought into a heated building the relative humidity will drop. The higher the air change rate, the lower the relative humidity. Due to the tendency of occupants not to open windows as much during the heating season [28] the reduced ventilation results in higher relatively humidity and a higher risk of dust mites and mold growth especially on poorly insulted building elements. MVHR is able to ensure an adequate ventilation rate and in poorly insulated buildings, the introduction of MVHR was shown to result in fewer house dust mites and better indoor air quality, improving the health of asthmatics [36,37]. Reduced humidity also helps prevent mold and fungi growth, as any cellulose rich material, such as wood, paper, wallboard, thermal and acoustic insulation, furnishings, will support mold growth if the humidity is high enough. What has not been extensively investigated is the relative humidity in naturally ventilated but highly insulated buildings and MVHR may not be essential in providing a dust mite-, mold- and fungi-free environment.

Furthermore, when providing high air change rates in conjunction with large temperature differences between indoors and outdoors MVHR has been associated with excessively low levels of relative humidity [12], which if experience over prolonged periods can cause dryness of the eyes, nose, and throat, and the sensitizing of mucus membranes, which can in turn result in elevated risk of virus infection and allergy attacks [38]. There are also concerns that mechanical ventilation systems "can be a source of indoor air quality problems" [27] mainly as a result of inadequate maintenance [11,27]. Therefore, while in theory MVHR can provide good air quality the practice may not always reflect the theory.

5. Energy Savings with MVHR

MVHR provides fresh air to the building in a controlled manner and by recovering the heat from the extracted air and using it to heat the fresh air it can reduce the overall heat loss. MVHR systems can be run only when the building needs heating, allowing the building to be free-running the rest of the year. MVHR also offers the opportunity for cooling when summer temperatures result in excessive heat.

MVHR systems are electrically operated and to enhance the energy performance of the building the energy used to run the MVHR has to be less than the heat recovered. The higher the heating requirements the more savings are possible. A comparison of the heating and ventilation energy requirements using a MVHR in Zurich (heating degree days 3400) and Milan (heating degree days 2200) compared to opening windows showed a reduction in energy of 4100/4350 kWh/a and 2460/2710 kWh/a respectively with MVHR [39]. While this study does not specify the exact heat loss and gains relevant to the building and the internal temperature selected for the comparison, which would affect the overall energy needs, it does illustrate the reduced benefit of MVHR in warmer environments.

The southern UK maritime climate is influenced by the Gulf Stream and results in warmer winters and cooler summers than the latitude would suggest. This is illustrated by the heating degree days for a selection of cities in the UK, Italy and Germany as shown in Table 1, whereby the heating degree days for the southern UK locations are less than the northern Italy locations. The table also lists the Climate Severity Index (CSI), referred to in the Passive-on program report [5] and developed by Markus *et al.* (1984) (refer to [40] for full definition of CSI). CSI characterizes the climate including heating degree days and solar radiation and hours of sunshine, and creates a more complete picture of the climatic impact on a passive solar design. While the southern UK climate is relatively warm, the downside in relation to passive solar designs is the limited solar gains due to the extensive cloud cover. This is reflected in the CSI, which nonetheless largely relates to the heating degree day figures, with the exception of London's winter CSI that appears higher than expected especially considering London's heat island effect. The CSI also records the cooling needs and it is worth noting that despite climate change impacting on future cooling needs, currently the summer CSI for all of the UK is virtually 0 while in southern Germany a minimal summer cooling requirement already exists.

Table 1. Heating degree days (degreedays.net) with 15.5 °C set temperature for selected locations in Germany, UK and Italy and the Climate Severity Index figures are taken from the Passive-on program report [5].

Degree days ranges	United Kingdom				Germany				Italy			
	Location	**Degree days**	**Winter Climatic Severity**	**Summer Climatic Severity**	**Location**	**Degree days**	**Winter Climatic Severity**	**Summer Climatic Severity**	**Location**	**Degree days**	**Winter Climatic Severity**	**Summer Climatic Severity**
< 2000	Plymouth	1802	-	-	-	-	-	-	Trapani	489	0.32	1.87
	London	1850	2.22	0.01					Rome	1085	0.83	1.19
	Brighton	1891	1.83	0.01								
	Cardiff	1971	-	-								
	Blackpool	1973	-	-								
2000–2500	Midlands	2234	2.36	0.00	Freiburg	2082	2.14	0.10	Milan	2003	1.81	0.46
	Belfast	2366	-	-	Frankfurt	2203	-	-				
	Glasgow	2439	2.59	0.00	Braunschweig	2247	2.56	0.05				
	Newcastle	2443	2.59	0.00	Bremen	2391	-	-				
					Berlin	2392	-	-				
					Hamburg	2410	-	-				
> 2500	Aberdeen	2654	-	-	Stuttgart	2512	-	-	-	-	-	-
					Dresden	2539	-	-				
					Nurnberg	2648	-	-				
					Augsburg	2827	3.31	0.00				

The impact of location and climate on the energy consumption was investigated by modeling the case study building using the Passivhaus Planning Package software edition 2004. The case study building selected for the study was designed to comply with the Passivhaus standard, it had beneficial orientation with good solar access to the living areas and the MVHR was modeled to have 92% recovery rate. Table 2 lists the percentage reduction in heating requirement for a selection of cities compared to Dresden. Dresden was selected as a comparison being the middle of the top range of heating degree day requirements in Germany. The modeling suggests that while the northern UK locations, such as Scotland, have similar heating requirement to Germany, the southern locations have significantly, up to about 50 percent lower, heating requirements.

Table 2. Comparison of annual heating requirement (kWh/m²a) of case study building in different locations.

Location	Annual heating requirement (kWh/m²a)	Percentage compared to Stuttgart
Plymouth	10.5	48.6%
London	14.1	65.3%
Glasgow	18.2	84.3%
Frankfurt	18.5	85.6%
Dresden	21.6	100%

Where the heating requirement is low, natural ventilation may be more energy efficient than MVHR. In order to compare the energy consumption of ventilating with and without MVHR, the case study building was modeled using the Passivhaus Planning Package 2004 climate files for Dresden, London and Plymouth. For each location three ventilation alternatives were modelled including:

- Passivhaus standard MVHR option with uniform temperatures of 18–21 °C throughout the building;
- A naturally ventilated option with uniform temperatures of 18–21 °C throughout the building;
- And a naturally ventilated option with non-uniform temperatures of 16 °C in bedrooms and 18–21 °C in living spaces.

The modeling temperatures were set a couple of degrees lower than those stipulated in the CIBSE guide in order to take into account the effect of superinsulation on the radiant heat exchange. As discussed above and as implied by the selection of 21 °C for the Passivhaus standard, as well as experienced in superinsulated houses [22], when walls and windows are well insulted and do not form sources of radiant coolth lower air temperature is felt as comfortable. The variations in the modeling were achieved by reducing the recovery rate to 0% to simulate the naturally ventilated free-running options and using the electrical consumption from the auxiliary electrical worksheet. As the PHPP software does not allow for differentiating the temperature of rooms, this effect was modeled by calculating the energy requirement for different temperatures and apportioning the rate of energy use to the relevant square meters of area heated at different temperatures. Table 3 illustrates the results for the London, Plymouth and Dresden climate modeling and shows for each location the base case, defined as the option with MVHR and uniform temperature of 21 °C throughout, and the energy requirement reduction or increase for the alternative options.

The modeling illustrates that the MVHR option is more energy efficient than a naturally ventilated option with uniform temperature throughout the building, but generally less efficient than a naturally ventilated option with differing temperatures. In particular, the following points can be noted in relation to the three locations modeled:

- Reducing the set temperature by 1 °C reduces the energy consumption by approximately 10% in colder climates and up to 14% in milder climates.
- In colder climates (such as in Dresden), a building with MVHR uses less energy than a naturally ventilated building if uniform temperature throughout the building is assumed. If non-uniform temperature is assumed in the naturally ventilated option, then modest savings can be made in naturally ventilated buildings if the upper temperature is maintained at 18–19 °C.
- In warmer climates (such as in Plymouth and London), a building with MVHR and uniform temperatures throughout uses less energy than a naturally ventilated building with uniform temperature throughout, but more energy than a naturally ventilated building with non-uniform temperatures.

Table 3. Variations in energy use in kWhr per annum in different climates and as a percentage of the base case in each climate

Location	**Plymouth**		**London**		**Dresden**	
Energy consumption for the base case with MVHR and uniform 21 °C	Energy use in kWh/a	Energy use as % of base case	Energy use in kWh/a	Energy use as % of base case	Energy use in kWh/a	Energy use as % of base case
BASE CASE MVHR and uniform 21 °C	2031	100%	2384	100%	3124	100%
Natural ventilation and uniform 21 °C	3087	152%	3566	150%	4657	149%
Natural ventilation and non-uniform temperature up to 21 °C	1690	83%	2143	90%	3149	101%
MVHR and uniform 20 °C	1737	86%	2078	87%	2796	90%
Natural ventilation and uniform 20 °C	2638	130%	3120	131%	4194	134%
Natural ventilation and non-uniform temperature up to 20 °C	1543	76%	1996	84%	2996	96%
MVHR and uniform 19 °C	1464	72%	1786	75%	2477	79%
Natural ventilation and uniform 19 °C	2199	108%	2682	113%	3736	120%
Natural ventilation and non-uniform temperature up to 19 °C	1397	69%	1852	78%	2846	91%
MVHR and uniform 18 °C	1219	60%	1513	63%	2168	69%
Natural ventilation and uniform 18 °C	1776	87%	2254	95%	3285	105%
Natural ventilation and non-uniform temperature up to 18 °C	1258	62%	1712	72%	2696	86%

Modeling assumes informed and well-behaved occupants who ventilate the buildings in the correct and most efficient way. This is often not the case and applies to both buildings with MVHR and naturally ventilated buildings, where occupants might turn off the MVHR, not replace filters, or conversely not open windows or block up vents. Modeling also depends on the assumptions made in and by the model and in the above example the outcomes depend on the particular building design. Despite all these potential limitation of abstract modeling, the modeling suggests that the design of buildings in warmer climates cannot simply adopt methods that work well in colder climates and expect these methods to yield the best possible results in a context they were not designed for.

6. Case Study Monitoring

The next question is whether the modeled results reflect the practice of buildings in use. The case study building data of over two years of monitoring would suggest it does.

The case study building consists of two flats in one block located in Cardiff, Wales and completed in 2008. The ground floor flat has a floor area of 44 m² and includes a north-facing bedroom, internal bathroom and a south-facing kitchen/dining/living room. The maisonette on the first and second floor has a floor area of 58 m² and includes a north-facing bedroom, internal bathroom with a rooflight, a south-facing kitchen/dining/living room on the first floor and a second bedroom on the second mansard floor. The construction is a timber frame with render and timber cladding external finishes and a zinc roof. The wall and roof construction comprises (from inside to outside) internal finishes, a 100 mm service void insulated with hemp insulation, vapor control layer and OSB board, 200 mm timber studs with hemp insulation, and 80 mm timber fiber insulation to take the external finish. The separating structure between the two flats is insulated for sound and thermal transmission with hemp insulation. The flats are run with electricity only and each flat has an independent heat store fed from an evacuated tube solar thermal array. Both flats were occupied by a single occupant who, in both cases, was an individual educated at postgraduate level with some limited theoretical or practical knowledge of sustainable buildings. The main difference between the ground floor flat and the upstairs maisonette construction affecting performance is the level of thermal mass. The ground floor slab consists of 200 mm concrete on 200 mm PU insulation and therefore provides significant thermal mass to the space, while the upper levels are a lightweight construction.

The monitoring of the case study building was undertaken over a period of consistent occupation over two years. The post-occupancy data collected included occupant profiles, energy consumption data collected at three to six monthly intervals, temperature measurements taken in all rooms at 30 min intervals and relative humidity measurements taken in one or two spaces per flat at 30 min intervals.

The main results of the energy monitoring showed a match of the modeled and monitored energy use in the ground floor flat (Table 4) but a significant difference in the maisonette. The ground floor monitored energy was slightly elevated compared to the modeled energy and could have been the result of the MVHR being left switched on for a large part of the first summer as the occupant had not understood that it could be switched off. Other behavior that might have impacted on the energy consumption could not be identified, even though the occupant did spend more hours than the average working person at home.

Table 4. Energy consumption of case study building

Energy consumption of case study building (primarily energy calculated using PHPP multiple for electricity)	Modeled primary energy consumption with PHPP software edition 2004	Monitored primary energy consumption over 2 years
Ground floor flat	101 kWh/m²a	109 kWh/m²a
First floor maisonette	93 kWh/m²a	37 kWh/m²a

An examination of the potential reasons for the discrepancy in relation to the maisonette identified the fact that the occupant had never switched on the MVHR and the average temperatures were lower than recommended by the Passivhaus standard. The occupant was operating the building with different temperatures in the different rooms, opening windows to refresh the air and using an electrical panel heater as required mainly in the living room and at times in the bedrooms. The average temperatures in the winter period in the bedroom where the occupant slept were between 16 °C and 17 °C, in the kitchen living area they ranged between 15.5 °C and 17 °C and in the mezzanine, which the occupant used as another living space, temperatures ranged from 17 °C to 20 °C. By using different areas of the home as required, the occupant succeeded in creating a comfortable environment with minimal heat input. It is worth noting that while the air quality was not measure the occupant reported the indoor air quality to be good and visitors including the researcher reported similar feedback.

Considering that the kitchen living area might need to be used instead of the mezzanine should the occupation of the dwelling change, an assessment was made in relation to the additional heat required to raise the temperature in the kitchen living space. Another 22 kWh/m²a primary energy would raise the temperature to 21 °C. In this case, the actual energy use would be in the order of 60 kWh/m²a versus 93 kWh/m²a modeled energy with MVHR and this naturally ventilated option without MVHR would still be more energy efficient than the option with MVHR.

7. Discussion

It could be argued that the Passivhaus standard building solution is robust because it incorporates a certain tolerance that ensures the building performs as modeled despite variations in occupant behavior. This suggestion is supported by Sunikka-Blank and Galvin's [41] meta-study comparing the calculated heating energy requirement to the post occupancy measured consumption of dwellings, which reported the Passivhaus case studies performed as modeled while other low energy schemes often underperformed. The same study also discusses how the calculated energy use of existing buildings, which are mainly naturally ventilated, often overestimates how much energy occupants used and how this phenomenon could be the result of incorrect calibration of calculation models or due to user behavior [41]. User behavior is well understood as having a significant impact on energy use and a building system should be conceived to minimize user behavior that could compromise the building performance. The Passivhaus system appears to do that. What we don't know is whether a highly energy efficient naturally ventilated building in mild maritime climates such as in the southern UK, which theoretically can perform better than a Passivhaus model with MVHR, would it be as tolerant of occupant mis- or non-optimal use.

Users understand the operation of the building to different degrees and they may or may not have an interest or wish for the building to perform well in terms of economics and or carbon emissions. In other words they have different levels of motivation and skill to operate a building efficiently.

Other related characteristics that ultimately affect the building performance include age and well-being, habit, conformity and determinedness, which can result in occupants adjusting internal temperatures throughout the building or in different rooms, using different parts of the building during different seasons and adjusting the ventilation as required. For instance, determined sustainability advocates might be ethically driven to heat their family home to 17 °C to reduce fuel use and reduce carbon dioxide emissions [42].

In terms of skills required to operate a building efficiently, the operation of a building with MVHR requires knowing how to vary fan rates from low to medium to high as required, in winter and summer switch the system on and off respectively, and change filters. The latter could be undertaken by a professional, adding to the maintenance cost but decreasing the level of knowledge and skill required by the occupant. If the MVHR integrates a heating or cooling mechanisms the occupants need to be aware that it can be set for specific temperatures and they need the ability to set a timer if present. While the latter activities need the occupants' attention infrequently and at planned intervals, varying the fan rate should respond to user needs and could be compared to opening and closing windows in a naturally ventilated building. The tolerance of the Passivhaus model is such that even if the MVHR runs at the highest level the energy consumption may still largely be within the modeled estimates, while if the windows in a naturally ventilated building are kept systematically open too long the heating requirements may rise significantly.

In this sense the Passivhaus model offers more tolerance than the current naturally ventilated systems. However, this does not imply a MVHR system is a totally misuse-proof system nor that a naturally ventilated option could not be designed to provide a similar tolerance. The occupant in the case study building failed to switch off the MVHR during the summer season and used excessive amounts of energy. Hancock [43] undertaking post-occupancy evaluations of dwellings in southern UK reported in a personal communication with the author that the MVHR installers hard-wired the MVHR so that they could not be switched off in the fear that once switched off the occupants would not switch the MVHR back on again. In southern UK this would mean that the MVHR would operate seven to nine months unnecessarily. The experience of occupants switching off ventilation systems, which were seen as unnecessary waste of money, and not switching them back on, resulted in the Slateford Green housing project in Edinburg installing passive vents rather than mechanically driven ventilation [44]. The increasing concern with energy costs could increase such occurrences. In the UK at least, occupants are assumed not to have the necessary aptitude to operate a MVHR efficiently but the safeguards implemented actually increase the energy consumption.

In relation to the maintenance of MVHR, in their review of the use of filters in air conditioning systems Beko *et al.*, [11] note that cleaning of ducts "it is very irregular and often neglected" despite national regulations in many countries requiring cleaning regimes to avoid recognized negative health impacts. This suggests that it cannot be taken for granted that less informed individuals would regularly incur a financial investment to change the filters of their MVHR.

Operating windows requires no special training, but understanding how to efficiently ventilate a space may need to be explained, as do the reasons why ventilation is necessary and why too much ventilation is wasteful. Dimitroulopoulou's [28] survey of ventilation habits in the UK noted that occupants were not aware of what trickle vents were for, suggesting even the most basic principles need to be explained. In contrast opening windows when the space feels stuffy and closing them when it is too cold are intuitive reactions. The challenge may be to design a window system that alerts the occupant to close the windows after a specific time (and possibly open them as well) or that automatically closes windows after a time. It is worth considering that a system that alerts the occupant to manually close the windows may give the occupant a feeling of control and therefore ownership and well-being, and may also act as an educational tool. A further challenge is to effectively educate occupants about how and why to ventilate their building.

In addition to knowledge, occupants may need to be motivated to adopt a more sustainable behavior. Hastings [23] notes that even though the highly energy efficient buildings he surveyed should have been comfortable at lower temperatures the occupants still heated between 21 °C and 22 °C. He does not however investigate why this was so. There are at least two possible explanations. Firstly, as suggested by Humphreys and Nicol [19], in controlled environments the comfort band shrinks and occupants are less tolerant of temperature deviations. Secondly, people are seldom motivated to question the models offered by society which portray a cool life of leisure free from the limitations of socks and jumpers and even less likely to adopt sustainable behaviors without being incentivized through psychological, economic or other means. While a discussion on motivation is outside the scope of this paper, it is critical to understand how to motivate occupants to behave more sustainably as simple changes, such as reducing the indoor temperatures, achieve significant carbon dioxide emission reductions, whether in a naturally or mechanically ventilated building.

Other Considerations

The Passivhaus Standard's aim is to provide an economically viable model of an ultra-low energy building and the cost of achieving the solution has to be considered. The natural ventilation option saves the capital cost of the installation of the MVHR [7]. In the case study building this was 3% of the total building cost, which could have been redeployed to increase the amount spent on insulation by 23% or spent on more opening vents to provide more controllable ventilation or on non-polluting materials. Furthermore, the MVHR is associated with maintenance costs to replace filters each year and it is liable to significant repair cost as a result of a malfunction. In the case study building, a microchip in the MVHR malfunctioned outside the warrantee period and its replacement cost 14% of the installation cost. Furthermore, in the UK where dwelling sizes are small relative to other European and American homes, the MVHR uses valuable space that could have other uses and increase the usable space and value of the property.

8. Conclusions

While the Passivhaus model is a robust model for ultra-low energy building in cold continental climates, the post-occupancy evaluation of a building in the mild southern UK climate designed to Passivhaus standards was shown to perform more efficiently and without compromising comfort without MVHR. This study also identified that research in field of thermal comfort supports the premise that thermal comfort can be achieved with non-uniform temperatures of 16–21 °C in a building as well as the uniform temperature of 20–21 °C as required by the Passivhaus model and that indeed variable temperatures are preferred by certain individuals. Furthermore, naturally ventilated buildings allow for user control which is also understood to enhance user comfort. Therefore, a naturally ventilated building in a mild climate is as appropriate a building solution, if not more appropriate, than a building solution with MVHR.

The implications of these results are important in relation to achieving UK government target of an 80% reduction in carbon dioxide emissions by 2050 from 1990 levels and for the construction of zero carbon emissions buildings by 2016 and the refurbishment of the existing building stock. While the inclusion of MVHR in new buildings may not significantly increase the capital cost, in the refurbishment of existing buildings the introduction of MVHR increases cost and involves major disruption. If an 80% reduction in heating energy can be achieved by installing adequate external insulation but no MVHR in the southern UK climate, as this study suggests, this would allow the building occupants to remain in the building during the building work to upgrade the building performance, reducing disruption and cost. In contrast to many of the Retrofit for the Future projects [45] that involved the installation of MVHR, a non-MVHR or passive Passivhaus alternative could more easily be adopted by mainstream construction and owner-occupiers. As climate change increases average temperatures, the mild climate experienced in southern areas is likely to be experienced further north making a naturally ventilated solution applicable to a wider geographical area.

The characteristics of such an alternative model would include features that were similar to the Passivhaus standard in terms of heating and overall energy targets, requiring high levels of fabric insulation and maximizing solar gains with suitable solar protection to prevent overheating. It would also include aspects unlike the Passivhaus standard such as reduced airtightness requirement to 1 ach, natural ventilation to all spaces with extracts in bathrooms and kitchens as required, and it might require more consideration about how the building is used and what the optimal internal configuration might be to maximize energy savings.

Optimizing this naturally ventilated low energy model could involve technical and design improvements to the ventilation system, a better understanding of the impact of internal room configuration on internal temperatures and therefore energy use, and a review of building materials to re-evaluate their potential impact on indoor air quality. Dynamic modeling tools would provide more refined modeling compared to the PPHP and be able to model the temperature in different rooms. Devising systems that ensure occupants open and close ventilation opening at suitable intervals to provide adequate fresh air is critical and might constitute an advanced model of trickle vent, automatic opening and closing mechanisms, new window designs or other manual or automatic systems.

In addition, it is necessary that occupants gain a better understanding of how buildings work. Most people have passed a driving test and operating basic building systems requires no more technical understanding than driving a car. Any ultra-low energy building model, Passivhaus or naturally ventilated, will require some basic understanding to ensure optimal operation. This understanding is however not always there [28,35], but the answer, if these models are to become mainstream, is not to attempt to build the fail-proof building but rather to educate users. Education would cover the building operation but also the impact of user habits such as the selection of cleaning materials or the impact of additional building work. Users remain key to an efficient operation of the building.

The Passivhaus model works well in cold continental climates. In warmer climates the sustainable solution is not to over-specify, by adopting existing models, but to optimize specification. The effort in fine-tuning existing models or developing alternatives representing more locally appropriate solutions is likely to result in benefits in terms of cost, carbon dioxide emissions, user preferences and mainstream uptake.

References

1. Department for Communities and Local Government (DCLG). *Building a Greener Future: Policy Statement*; DCLG: London, UK, 2007.
2. Eine Starke Lobby für ein Starkes Konzept (in German). Available online: www.ig-passivhaus.de/index.php?group=1&level1_id=65&page_id=65&lang=de (accessed on 16 July 2012).
3. Passipedia. Energy Use—Measurement Results. Available online: http://www.passipedia.org passipedia_en/operation/operation_and_experience/measurement_results/energy_use_measurement_results (accessed 06 January 2013).
4. UK Government. *Climate Change Act 2008*; The Stationery Office: Norwich, UK, 2008; Chapter 27.
5. Informationen zum Passivhaus—Was ist ein Passivhaus (in German) Available online: www.passiv.de/de/02_informationen/01_wasistpassivhaus/01_wasistpassivhaus.htm (accessed on 18 July 2012).
6. Communities and Local Government. *The Code for Sustainable Homes. Setting the Standard in Sustainability for New Homes*; Communities and Local Government Publications: Wetherby, UK, 2008.
7. Ford, B.; Schiano-Phan, R.; Zhongcheng, D. *Design Guidelines for Comfortable Low Energy Homes. Part 1. A Review of Comfortable Low Energy Homes*; Passive-on: Nottingham UK, 2007. Available online: www.passive-on.org/CD/1.%20Technical%20Guidelines/Part%202/Passivhaus%20UK/Part%202%20-%20UK%20Passivhaus%20in%20Detail.pdf (accessed on 16 July 2012).
8. Passivhaus Institute. *"Zertifiziertes Passivhaus" Zertifizierungskriterien fuer Passivhauser mit Wohnnutzung* (in German); Passivhaus Institute: Darmstadt, Germany, 2012.
9. Zero Carbon Hub. *Mechanical Ventilation with Heat Recovery in New Homes*; Report for Ventilation and Indoor Air Quality Task Group: Keynes, UK, 2012.
10. Schiano-Phan, R.; Ford, B.; Gillott, M.; Rodrigues, L. The passivhaus standard in the UK: Is it desirable? Is it achievable? In *Proceedings of the 25th Conference on Passive and Low Energy Architecture*, Dublin, UK, 22–24 October 2008.
11. Beko, G.; Clausen, G.; Weschler, C. Is the use of particle air filtration justified? Costs and benefits of filtration with regard to health effects, building cleaning and occupant productivity. *Build. Environ.* **2008**, *43*, 1647–1657.
12. Feist, W.; Schnieders, J.; Dorer, V.; Haas, A. Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. *Energy Build.* **2005**, *37*, 1186–1203.
13. Minergie. *The Minergie-Standard for Buildings*; Minergie: Bern, Switzerland, 2010. Available online: www.minergie.ch/tl_files/download_en/Faltblatt_Minergie_Standard_e.pdf (accessed on 22 July 2012).

14. Rocky Mountain Institute. *Rocky Mountain Institute Abundance by Design*; Rocky Mountain Institute: Snowmass, CO, USA, 2007.
15. Baker, N.V.; Standeven, M.A. Thermal comfort in free-running buildings. *Energy Build.* **1996**, *23*, 175–182.
16. Brager, G.S.; de Dear, R.J. Thermal adaptation in the built environment: A literature review. *Energy Build.* **1998**, *27*, 83–96.
17. Brager, G.S.; de Dear, R.J. A standard for natural ventilation. *ASHRAE J.* **2000**, *42*, 21–28.
18. Nicol, J.F. *Thermal Comfort—A Handbook for Field Studies Towards an Adaptive Model*; University of East London: London, UK, 1993.
19. Nicol, J.F.; Humphreys, M.A. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy Build.* **2002**, *34*, 563–572.
20. Nicol, J.F.; Humphreys, M.A. New standards for comfort and energy use in buildings. *Build. Res. Inf.* **2009**, *37*, 68–73.
21. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). *Standard 55 Thermal Environment Conditions for Human Occupancy*; ASHRAE: Atlanta, GA, USA, 1992.
22. Vale, B. *The Autonomous House*; Thames and Hudson: London, UK, 2000.
23. Hastings, S.R. Breaking the "heating barrier": Learning from the first houses without conventional heating. *Energy Build.* **2004**, *36*, 373–380.
24. Baker, N. Designing for Comfort. Recognising the adaptive urge. In *Proceedings of the Cooling Frontiers Symposium*, Tempe, AZ, USA, 4–7 October 2001.
25. Heschong, L. *Thermal Delight in Architecture*; MIT Press: Cambridge, MA, USA, 1979.
26. Chartered Institution of Building Services Engineers (CIBSE). *Guide B1 Heating*; The Chartered Institution of Building Services Engineers: London, UK, 2002.
27. World Health Organization (WHO). Development of WHO guidelines for indoor air quality. Presented at *a Working Group Meeting*, Bonn, Germany, 23–24 October 2006.
28. Dimitroulopoulou, C. Ventilation in European dwellings: A review. *Build. Environ.* **2012**, *47*, 109–125.
29. WHO. *WHO Guidelines for Indoor Air Quality: Selected Pollutants*; WHO Regional Office for Europe: Copenhagen, Denmark, 2010.
30. American Conference of Governmental Industrial Hygienists (ACGIH). *Documentation of the Threshold Limit Values and Biological Exposure Indices*, 6th ed.; American Conference of Governmental Industrial Hygienists: Cincinnati, OH, USA, 1991.
31. Lambertsen, C.J. *Carbon Dioxide Tolerance and Toxicity*; University of Pennsylvania Medical Centre, Institute of Environmental Medicine: Philadelphia, PA, USA, 1971.
32. Seppänen, O.A.; Fisk, W.J.; Mendell, M.J. Association of ventilation rates and CO_2 Concentrations with health and other responses in commercial and institutional buildings. *Indoor Air.* **1999**, *9*, 226–252.
33. Newell, T.; Newell, B. *Comfort Conditioning and Indoor Air Quality*; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.: New York, NY, 2011.

34. National Toxicology Program (NTP). *Final Report on Carcinogens. Background Document for Formaldehyde*; U.S. Department of Health and Human Services, Public Health Service: Research Triangle Park, NC, USA, 2010.
35. Engvall, K.; Wickman, P.; Norbäck, D. Sick building syndrome and perceived indoor environment in relation to energy saving by reduced ventilation flow during heating season: A 1 year intervention study in dwellings. *Indoor Air* **2005**, *15*, 120–126.
36. Harving, H.; Korsgaard, J.; Dahl, R. Clinical efficacy of reduction in housedust mite exposure in specially designed, mechanically ventilated healthy homes. *Allergy* **1994**, *49*, 866–870.
37. Warner, J.A.; Frederick, J.M.; Bryant, T.N.; Weich, C.; Raw, G.J.; Hunter, C.; Stephen, F.R.; McIntyre, D.A.; Warner, J.O. Mechanical ventilation and high-efficiency vacuum cleaning: A combined strategy of mite and mite allergen reduction in the control of mite-sensitive asthma. *J. Allergy Clin. Immunol.* **2000**, *105*, 75–82.
38. Palmer, A.; Rawlings R. *Building-Related Sickness Causes, Effects, and Ways to Avoid It*; Building Services Research and Information Association: Bracknell, UK, 2002.
39. Kriesi, R. Comfort ventilation—A key factor of the comfortable, energy-efficient building. *REHVA J.* **2011**, *3*, 30–35.
40. Clarke, J.A. *Energy Simulation in Building Design*; Butterworth Heinemann: Oxford, UK, 2001.
41. Sunikka-Blank, M.; Galvin, R. Introducing the prebound effect: The gap between performance and actual energy consumption. *Build. Res. Inf.* **2012**, *40*, 260–273.
42. Simper, E. Low carbon lifestyles. *Ethical Consum.* **2006**, *103*, 23.
43. Hancock, M. Faculty of Technology, Oxford Brookes University. Personal communication, 2012.
44. Sassi, P. *Strategies for Sustainable Architecture*; Taylor & Francis: Abingdon, UK. 2006.
45. Retrofit for the Future. Available online: www.retrofitforthefuture.org/ (accessed on 16 July 2012)