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Health effects of energy efficient design strategies of passive house standard: a cross country analysis

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Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:
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Knowledge of the effects of demand for energy security, climate change, and the rising energy prices have aroused significant changes in construction practices, design thinking and legislation, aimed at lessening emissions of carbon dioxide and energy consumption within the building sector. One of the major features of Passive House technologies is the incorporation of airtight envelope, which reduce uncontrolled airflow through the structure of the building, while this reduces heat loss due to infiltration, there is a growing concern by the public due to alleged adverse health effects. With net-based post occupancy questionnaire, interviewer-administered questionnaire (face to face) and semi-structure interview, this study investigates if occupants of Passive Houses experience different health, wellbeing and housing satisfaction in their current dwellings as compared to when living in their previous houses, and if associations with indoor air quality exist. 92 occupants of Passive Houses from 6 countries completed the net-based questionnaire, 6 occupants in Munich, Germany completed interviewer administered questionnaire and 4 Passive House experts in Germany were interviewed. Experts and occupants were interviewed to gain information on perceived occupants' health, wellbeing, indoor air quality, thermal comfort and adaptability of Passive House technologies to different climates. Occupants' self-reported health and their household improved frequently ($p < 0.05$) in their current houses (Passive House) than in previous dwellings (82% vs. 42%). Occupants rated perceived indoor air quality and thermal comfort significantly higher ($p=0.03$), prevalence of Sick Building Syndrome Symptoms was again higher in previous dwellings except dry eyes that was relatively high in Passive Houses (8.2%). As humidity in Passive Houses is lower, there is a possibility that occupants reported relatively high prevalence of dry eyes.

Keywords: Passive Houses, Self-health report, Sick Building Syndrome Symptoms, Indoor air quality, Perception, Thermal comfort, Prevalence, health and wellbeing

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1.0. Introduction

1.1 Background

Over the years, energy demand has increased considerably in the world. Furthermore, the European Union Commission on Climate Change in 2017 reports that one of its major priority task is to integrate all efforts to address global warming, particularly focusing on reducing greenhouse gasses. In the directive for energy efficiency in the built environment, the Commission states that the building sector should lessen its energy consumption to decrease CO_2 emissions. The Commission proposes a target of 20% increase in energy efficiency by 2020 (European Commission 2007).

To reach these targets, it is expedient to incorporate many different activities towards the same goal. One crucial area is the building sector, which accounts for almost 40% of total energy use and 36% of CO_2 emissions in the EU (European Commission 2007). According to the building performance directive, near-zero energy buildings (NZEB) are one of the germane components to reach these targets. Several established labels for energy-efficient buildings are already in place including a well-known Passive House Standard. The target to achieve high energy performance has resulted into the design of Passive House concepts, where the approach to lessen the demand for energy is followed to such extents, that a central heating system is not required (Evert 2008). There is a growing interest in Passive Houses and it has gained rapidly in popularity. Many Passive Houses have been built in Germany, United Kingdom, Ireland, and other Non-EU countries follow USA, Australia and Canada, while the interest in passive renovation and Passive Houses is increasing in China as well.

Passive House is known by its very low air leakages, low ventilation losses through the building envelope and low transmission losses, which is commonly achieved through efficient heat exchange between exhaust and supply air (Schneider and Feist 2010, Passive House Institute 2011). Passive

House is designed to be heated mainly by the heat from solar radiation and the internal heat gains from the occupants, and their activities in the building. During the heating season, there are usually some kind or complementary heating system installed to meet the indoor climate requirement (Feist 2006, Passive House Institute 2011). Moreover, the incorporation of an airtight envelope is one of the fundamental features of Passive House Standard and it helps to minimize uncontrolled airflow through the structure of the building.

Whilst the airtight envelope technology lessens heat loss attributed with infiltration, there is a growing concern that the requirements for purpose provided ventilation have not received adequate attention (Hasselaar 2008, Steve 2014). On the one hand, over dependence on mechanical ventilation systems to achieve proper levels of ventilation volumes, has resulted in anxiety and significant concern regarding the potential adverse effects of Passive House design strategies on the quality of indoor air (Rohdin et al. 2014). On the other hand, high energy efficient building such as Passive Houses can generate social and environmental benefits (Evert 2008). Passive House design and technologies bring benefits to environmental protection and development, including energy saving for artificial heating, lighting, ventilation and air conditioning. Due to optimization of design for thermal comfort and daylight, Passive House technologies and design offer building occupants better indoor environment, thermal comfort, visual connection to outdoors and indoor air quality leading to a higher level of wellbeing, healthier quality of life and comfort for its users which generally improve health by reducing sicknesses and deaths caused by a poor indoor climate (Evert 2008, Feist et al., 2010, Passive House Institute 2011).

This study will investigate the effects of Passive House technologies on the health and well-being of its users across six countries. As WHO aptly explain, the significance of building in health and environmental policy is evident (WHO 2004). The WHO's resolution on health and environment has called for the urgent needs to protect public health from the adverse effects of notable hazards that are related to environment such as those emanating from housing and climate change (WHO 2004).

Not only has there been insufficient research in high energy efficiency of Passive Houses and its potential impacts on the environment, but with the advent of socio-economic development of Passive House technologies, the effects of energy efficient design strategies of Passive Houses on the health of users are a current and relevant topic for educators and researchers. Following a statement by Innovation and Growth Team (2010), there is a worrying lack of knowledge regarding indoor air quality in energy efficient buildings, which should be addressed as a priority. This knowledge gap is clearly indicated by Cramp et al. (2009:6)

> *"There appears to be an urgent need for research into the performance of highly energy efficient homes with respect to the quality of the internal environment, ventilation systems used and the impact on the health and wellbeing of occupants".*

This study emerged by addressing this gap with the principal aim of investigating and evaluating the effects of energy efficient design strategies of Passive House Standard on the perceived occupants' health and wellbeing, using a combination of Net-based post-occupancy survey, Interviewer-administered questionnaire (face to face) and complementary interviews to investigates two questions:

1. What are the impacts of energy efficient design strategies of Passive House Standard on perceived occupants' health and well-being?
2. As compared to active (convectional) buildings, how often do building-related health symptoms occur in Passive Houses?

The aim can be further subdivided into specific objectives:

1. To assess the effects of the condition, modernity and performance of mechanical ventilation systems in Passive Houses on the perceived occupants' health and well-being.
2. To identify the prevalence of building-related health symptoms in occupants' previous dwellings as compared to the prevalence in their present dwellings (Passive Houses).
3. To compare the health of occupants in Passive Houses with their health condition in previous dwellings.

This study uses a combination of post occupancy survey and data from Passive House tenants, expert meeting and housing association to evaluate the health status of Passive House users, using the frequency of occurrence of commonly reported building-related health symptoms such as asthma, common cold as health indicator. The post occupancy survey used is an example of a standardized epidemiological survey that has been used widely in many countries. An epidemiological method is useful for describing the perception and experiences of tenants regarding indoor environment and it is very effectual when evaluating the results such as when measuring energy efficiency (Andersson 1998), or when comparing the prevalence of sick building syndromes in different building designs. By doing this investigation, general recommendations can be given to policy makers, companies or persons developing energy efficiency buildings such as Passive House Standard.

1.2 Outline of Thesis Structure

Following the introduction, this thesis will first contextualize the study by exploring relevant literature on the effects of energy efficient design strategies of Passive Houses under three subsections in Chapter 2. The first section will define what passive houses are, the concepts of Passive Houses, its historical perspectives, certification and Passive House retrofit. The second compares exposure guidelines and describing their relevance to health. The third section will discuss the significance of Passive House technologies on indoor environmental qualities. In Chapter 3, efficient versus effective design of Passive House indoor environment will be discussed, while Chapter 4 gives an account of the study methodology. A cross country analysis was then performed which integrated and assimilated the knowledge gained from the study population into different sections, specifically, indoor environmental qualities and its effects on health of occupants, knowledge and perception of Passive House experts; the results of which are presented in Chapter 5. The findings of the thesis are then compared with previously published materials on the topic, which formed the basis of the discussion in Chapter 6. This chapter has presented an overview of the purpose of this study and outlined the aims, objectives and the structure of the thesis. The subsequent sections will now present an overview of the concepts of Passive Houses, criteria for Passive House Standard, certification, PHPP and EnerPHit Standard of Passive Houses, the effects of Passive House technologies on indoor climate will be discussed.

2.0. Literature review

The literature review was conducted in a manner that was fair and impartial, as suggested by Pritchard (1994). Literature was collected from rich sources, including many opinions ranging from Passive House Institutes to peer reviewed academic journals and topic editorials, published in media such as building technology and health publications, books, government publications, articles and conference proceedings. A range of databases were used including PubMed, Wiley, Science-direct, SpringerLink, construction information services and Google Scholar. During the literature search, academic literature was considered most important and was consulted to find information considering the health, environmental and technical aspects of Passive House Standard. However, over the years, there have only been approximately four significant academic research studies conducted on Passive House technologies. Trying an extensive yet scholarly search for this review, research and study reports were limited to peer reviewed, databases and scholarly journals, news articles and dissertations. Key terms such as "energy efficient building, passive houses and energy efficiency design strategies", "indoor climate, thermal comfort, health and well-being, Sick Building Syndrome" were used to narrow the search. I later restricted the inclusion of research articles involving occupants in well-built and certified Passive Houses in response to a gap in the literature regarding the effects of Passive House technologies on indoor air quality, health and well-being of occupants. Despite the growing expertise, two recurring gaps in the research have been identified with broad implications as follows:

- *Technology:* Most of the studies focus on Passive Houses with design defects or with poorly installed heat recovery ventilation systems and dwellings with high occupancy and smaller dimensions of rooms (Hasselaar 2008, Rohdin *et. al* 2014, Steve 2014)

- *Methods*: Small sample size, inadequate knowledge of background factors and medical history of allergic diseases (Hasselaar 2008, Steve 2014).

In response to these gaps, technology, method, effects of certified Passive Houses on health and well-being of occupants is the focus of this study. The study uses a large sample size and combination of methods including interview with experts and post-occupancy questionnaire to survey occupants in standardized Passive Houses, with a background questions on the medical histories of respondents, household member and other factors such as smoking that can exacerbate the symptoms used as health indicator. While designing this study, (Rohdin *et. al 2014*) was identified as the relevant and the most recent research regarding health effects of Passive House technologies.

2.1. Historical Review of Passive Houses

The concepts of energy recovery ventilation, superinsulation, high performance windows, managing solar gain and airtight originated in the Canada and United States in early 1980s, a reaction to the Organization of the Petroleum Exporting Countries (OPEC) oil embargo. Interest in conservation dwindled in the United States for several years. During that period, the Europeans sifted the application of these principles and opt for high-performance products. Swedish scientist Bo Adamson and a German physicist Wolfgang led the effort to refine the concepts and develop the strategies and design techniques of "passivhaus" performance metric. In 1990, the first Passivhaus residences were built in Darmstadt, Germany and occupied by clients the year that follow. Ever since,

> *"the Passive House Standard has gained rapidly in popularity, with over 20,000 Passive Houses in existence worldwide. More than 13,500 Passive Houses have been built in Germany alone, many of which have been certified according to strict Passive House Institute criteria. These numbers are on the rise"* (Passive house Institute 2014:2).

2.2. Description of Passive house Standard

Globally, buildings are responsible for 40% of energy consumption, with a large proportion of this related to the residential sector (European Commission 2007). Proven knowledge and technologies emerge to reduce energy consumption by buildings. One of these methodologies is Passive House Standard, resulting in ultra-low energy buildings and the concepts is appropriate for all climate.

The concept of Passive House was developed by Adamson and Feist, and it has been described as a building "in which a comfortable interior climate can be maintained without active heating and cooling systems" (Passive House Institute, 2011a). The features of Passive Houses are optimised for local climatic conditions. For instance, to enable comfort in summer, more attention is placed on passive shading of windows in hotter climate. Passive Houses can be found in the South and North America, Asia, the United Kingdom and Africa. Moreover, the Passive House Standard is not a regulation, but a certification system and a methodology for developing buildings with a very high energy saving potentials (Feist 2006, Jimmefors 2014). Passive House concepts are not limited to residential sector but also to public and municipality, including commercial and industrial buildings. In addition, Passive House Standard gives room for cooling-related and space heating energy savings up to "90% compared with typical building stock and over 75% compared to average new builds" (Feist and Schneider 2010:145).

2.3. Criteria for Passive House Standard

Passive Houses are generally known by minimum energy use coupled with high level of thermal comfort. Moreover, in the case of new builds Passive House Standard provides magnificent cost-effectiveness. The categories Passive House Premium, Plus or Classic can be achieved based on the generation of renewable energy and renewable primary energy. Thus, as indicated in (table 2.1), before a house can be regarded as a Passive House it has some certain criteria to meet.

Table 2.1 Passive House criteria, (Passive House Institute 2011b)

			Criteria[1]			Alternative Criteria[2]
Heating						
Heating demand	[kWh/(m^2a)]	≤	15			-
Heating load[3]	[W/m^2]	≤	-			10
Cooling						
Cooling + dehumidification demand	[kWh/(m^2a)]	≤	15 + dehumidification contribution[4]			variable limit value[5]
Cooling load[6]	[W/m^2]	≤	-			10
Airtightness						
Pressurization test result n_{50}	[1/h]	≤	0.6			
Renewable Primary Energy (PER)[7]			Classic	Plus	Premium	
PER demand[8]	[kWh/(m^2a)]	≤	60	45	30	±15 kWh/(m^2a) deviation from criteria...
Renewable energy generation[9] (with reference to projected building footprint)	[kWh/(m^2a)]	≥	-	60	120	...with compensation of the above deviation by different amount of generation

Energy for dehumidification, electrical appliances, lighting, cooling and heating is included in the criteria. Moreover, the limit value applies for administrative, residential and typical educational buildings. After consultation with the Passive House Institute, the limit value can be exceeded in case of an extremely high electricity demand.

2.3.2. EnerPHit Standard

Due to different challenges such as social, political and economic issues, the criteria above are almost impossible to accomplish in older buildings. New Passive Houses can be designed, built and dimensioned with the criteria in mind. However, this is not possible for older houses. In such houses, the renovation to "EnerPHit Standard" with components of passive house for all pertinent structural elements result in substantial improvements regarding structural integrity, thermal comfort, energy requirement and cost-effectiveness. According to Passive House Institute (2011b), to accomplish the EnerPHit-Standard, the structural element of the building must comply with the criteria in table 2.2.

The criteria indicated in Table 2.2 as a rule, must be met before a Passive House can be certified, while table 2.3 contains alternative criteria to meet for energy demand (Jimmefors 2014).

Table 2.2 EnerPHit criteria for the building component method (PHI 2011b)

Climate zone according to PHPP	Opaque envelope[1] against...				Windows (including exterior doors)					Ventilation	
	...ground	...ambient air			Overall[4]			Glazing[5]	Solar load[6]		
	Insulation	Exterior insulation	Interior insulation[2]	Exterior paint[3]							
	Max. heat transfer coefficient (U-value)			Cool colours	Max. heat transfer coefficient ($U_{D/W,installed}$)			Solar heat gain coefficient (g-value)	Max. specific solar load during cooling period	Min. heat recovery rate[7]	Min. humidity recovery rate[8]
	[W/(m²K)]			-	[W/(m²K)]			-	[kWh/m²a]	%	
Arctic	Determined in PHPP from project specific heating and cooling degree days against ground.	0.09	0.25	-	0.45	0.50	0.60	$U_g - g*0.7 \le 0$	100	80%	-
Cold		0.12	0.30	-	0.65	0.70	0.80	$U_g - g*1.0 \le 0$		80%	-
Cool-temperate		0.15	0.35	-	0.85	1.00	1.10	$U_g - g*1.6 \le 0$		75%	-
Warm-temperate		0.30	0.50	-	1.05	1.10	1.20	$U_g - g*2.8 \le -1$		75%	-
Warm		0.50	0.75	-	1.25	1.30	1.40	-		-	-
Hot		0.50	0.75	Yes	1.25	1.30	1.40	-		-	60 % (humid climate)
Very hot		0.25	0.45	Yes	1.05	1.10	1.20	-		-	60 % (humid climate)

Table 2.3 EnerPHit criteria for the energy demand method as an alternative to Table 2.3 (PHI 2011c)

Climate zone according to PHPP	Heating	Cooling
	Max. heating demand	Max. cooling + dehumidification demand
	[kWh/(m²a)]	[kWh/(m²a)]
Arctic	35	equal to Passive House requirement
Cold	30	
Cool-temperate	25	
Warm-temperate	20	
Warm	15	
Hot	-	
Very hot	-	

To meet these criteria, Feist and Schneider (2010:144-145) develop five major components upon which the concept of Passive house is based:

1. **Magnificent thermal insulation, low window heat losses including thermal bridge free design**

Table 2.4 below contains the translation of the magnificent thermal insulation into values. These values apply to the structural elements of the building envelop. In addition to the criteria, certain criteria are set for cold bridges to meet, such as Ψ < 0.01 W/m·K. Breach in thermal insulation results to cold bridges, and the breach usually occur around window leading to building knots-the meeting point of wall and floor. Boer et al. (2009) recommends that in the construction of passive houses, the glazing should be less than 50% of solar heat-gain coefficients, which is the total amount of sunlight entering through the glass.

Table 2.4 level of insulation for elements of the building envelope (De Boer et al. 2009)

Building element	Passive house level of insulation
Wall, roof and floor	$6.5 < R_c < 10$ [$m^2 \cdot K/W$]
Window casings, doors	<0.8 [W/ $m^2 \cdot K$]
Window glazing	<0.8 [$W/m^2 \cdot K$]

A thick layer of insulating material is needed to reach the values indicated in table 2.4. When conventional insulating materials like EPS or wool are used for floor, roof and wall elements, the thickness can be as much as 30 cm. Conversely, the thickness can be reduced to roughly 20cm with the use of low thermal conductivity and insulating materials such as hard foam panels (Passipedia 2011, Jimmefors 2014).

The U-value for glass casing and glazing are reached by utilizing triple glazing in casings appropriate with a thermal interruption to avert cold bridges. Figure 2.1 shows an example of a window casing that is fitted with triple glazing. The casing is made of wood, and sometimes plastic, aluminum or fusion of materials. In figure 2.1, the circles indicate the thermal interruptions. The interruptions are produced from hard foams, decreasing the heat transfer through the casing resulting into a low U-value of 0.78/W/m^2. K. The window relatively gets heavy because of the triple glazing, which should be considered while designing the house. The structure of the wall should be well built so it can carry the weight of the windows.

Figure 2.1 Passive House window and casing (Overbeek 2010)

2. **Airtight building envelope**

Another basic component of Passive house is an airtight building envelope. An airtight building envelope is procured by thorough construction by which air leakage and air gaps can be prevented. All the gaps and joints are that can leak out air are filled or covered during the construction or retrofitting. Figure 2.2 is an example of how the joints between the wooden panels are covered with tape. The insulating material underneath the panels are sealed with foil and taped to prevent air leakage. Blower door test is used to examine the air tightness of Passive House.

Figure 2.2 sealing joined with tap (DWA 2009)

3. **Highly efficient heat recovery with ventilation system**

Ventilation system is essential in Passive House, it ensure a suitable indoor environment because of the air tightness. Moreover, balanced ventilation is used because it helps to prevent ventilation heat losses (Passive House Institute 2011a). Ventilation is balanced by blowing fresh air into the rooms while the old air is extracted. Fresh air from the outside the building is filtered before it gets into the indoor, thus enhancing the quality of the indoor air.

The "balanced ventilation system is equipped with a heat recovery system: a counter flow heat exchanger in which extracted warm air from inside the house is used to preheat the fresh air coming from outside. There is no strict rule for the efficiency of the heat recovery unit.

> *The Passive House Institute however indicates that the efficiency should be above 80%"* (Passive House Institute 2011a).

As Boer et al. (2009:16) aptly put it, "systems with higher efficiencies are available up to 95% and could therefore also be used".

4. The passive use of solar energy

One of the basic concepts of passive houses is to insulate the houses to the level at which there is little or no need for supplementary space heating. Solar heat is optimally used by orientating the building to the south. The heat generated from the sun is preserved by the thick insulating layer within the house. Very low temperatures or little sunlight during the days is adequate to heat the incoming fresh ventilation air that helps maintain the building at a comfortable temperature (Feist and Schneider, 2010).

5. Internal heat gains

Internal heat gain is another crucial factor for Passive House. Electrical appliances such as refrigerators, computers, televisions and others generate heat. The heat also helps to maintain balance of Passive houses Feist and Schneider (2010). Figure 2.3 and 2.4 depict the energy balance in Passive House.

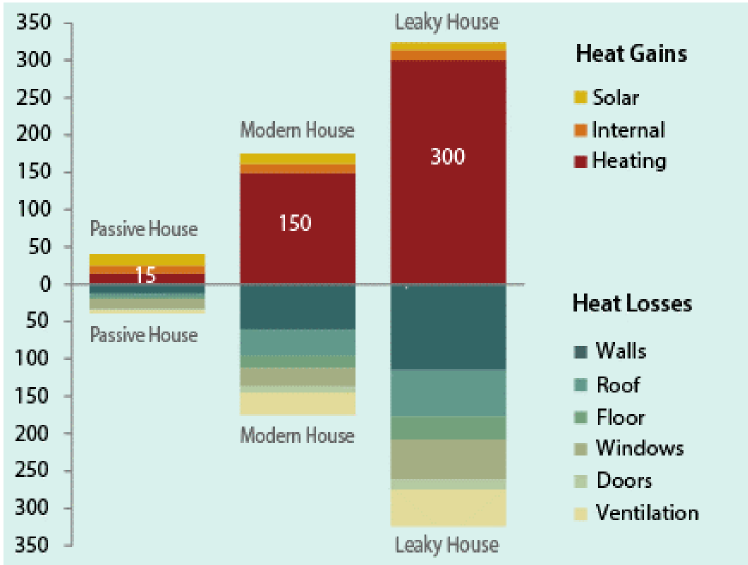

figure 2.3 Heat gains losses by house type: kW/m2a (adapted from PHPP 2015)

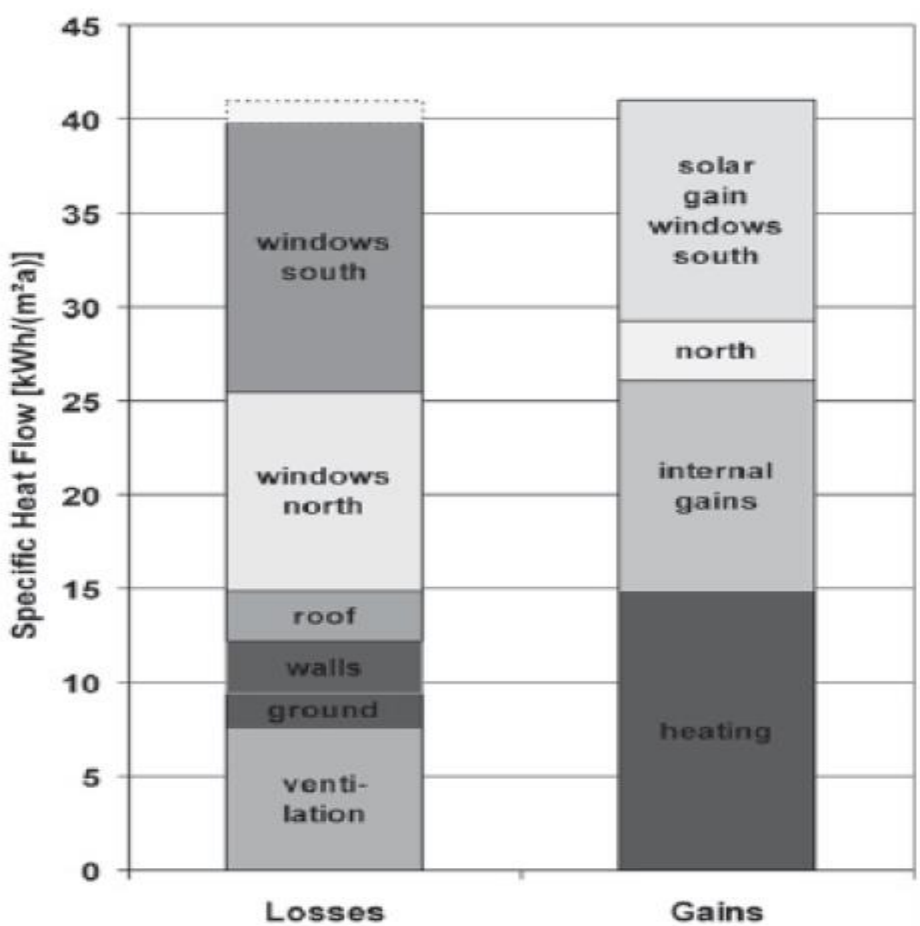

Figure 2.4 Energy balance of a Passive House (Feist and Schneider 2010)

2.4. Passive House Planning Package 2007 (PHPP)

Passive House Institute designed a tool in 2007 to determine whether a Passive House meets the criteria. The blower test is generally used to test whether the building meets the air tightness criteria. PHPP is used to text compliance of Passive House with other criteria. The entire Passive House can be modelled by PHPP which uses Microsoft Excel calculation method. PHPP shows if the criteria are met as soon as all the information such as the surfaces, cold bridges, U-values is entered. Figure 2.4 below shows the Passive House verification sheet. On the figure below, the right column indicates whether the requirements for the certification are met. Moreover, a "yes" on the cells shows that they can begin the certification process. PHPP is a calculation method used for the certification of both newly built Passive Houses including the Passive House retrofits.

Treated Floor Area:	120,8	m^2		
	Applied:	Monthly Method	PH Certificate:	Fulfilled?
Specific Space Heat Demand:	14	$kWh/(m^2a)$	15 $kWh/(m^2a)$	Yes
Pressurization Test Result:	0,6	h^{-1}	0,6 h^{-1}	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	113	$kWh/(m^2a)$	120 $kWh/(m^2a)$	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	60	$kWh/(m^2a)$		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		$kWh/(m^2a)$		
Heating Load:	17	W/m^2		
Frequency of Overheating:	0	%	over 25 °C	
Specific Useful Cooling Energy Demand:		$kWh/(m^2a)$	15 $kWh/(m^2a)$	
Cooling Load:		W/m^2		

figure 2.4 Passive House verification sheet (Boer et al., 2009)

2.5. Passive House renovation

Section 2.2 talks about the four concepts of Passive Houses, these concepts also apply to Passive House retrofit. As previously mentioned in section 2.2, the requirements for new houses are too strict for old buildings. Thus, this section talks about the major criteria for Passive house retrofit.

Insulation

One of the major components of Passive house concepts is thermal insulation, besides the changes in the U-value for windows, there are little or no changes to the criteria of table 2.4 '$U_{w,\ installed} \leq 0.85$ W/m2·K', which is the average value of all windows installed in the building. According to Passive House Institute (2011c), some windows can have higher U-values provided the average is below 0.85.

Air tightness and ventilation

Another seemingly hard component to enact in existing building is air tightness. Hence, air leakage of $n50 \leq 0.6/h$ is the criterion set as a 'target value', while $n50 \leq 1.0/h$ is the limit value. Heat recovery with a balanced system is need for ventilation. Moreover, a minimum of 80% ($\eta HR,eff \geq 80$ %) is needed for effective heat recovery unit and 0.45 Wh/m_3 is needed for electrical efficiency of the ventilation system (Feist and Schneider 2009, Passive House Institute 2011c). The required heating load of 10 W/m_2 is due to (1 m_3/h per m_2) of ventilation flow rate and 55°C as maximum inlet temperature.

2.6. Passive house renovation energy

Passive house retrofit have a tremendous effect on the material CED, mostly when new masonry is used to replace the outer wall of the existing cavity wall structure. Hence, the amount of energy that is saved over time by Passive house retrofit will certainly compensate for the cost of renovation (Feist and Schneider 2009). For Passive house retrofit, the amount of energy saving is higher because of the advanced building's air tightness, ventilation volume and effective insulation system of other elements of the house envelope. All these factors together increase the emission and energy savings of Passive house retrofit.

2.7. Passive house certification

Passive house criteria aim to ensure energy efficient building and before a building can be certified by Passive House Institute, all the criteria must be met. The figure 2.4 above contains the first three requirements for Passive house certification. For heating, the net annual energy may not exceed 15kWh/m_2a (54 MJ/m_2a). Following this, the total load for heating must not exceed 10W/m_2. In addition to this requirement, the primary energy demand for hot water, household electricity and heat must not be more than 120kWh/m_2a (432MJ/m_2a). The final criteria to meet is the requirement for ventilation $n50<0.6$ (Passive House Institute 2011c).

2.7.1. Certification process

To ensure the quality of official Passive House buildings and practitioners, a series of certification processes (**figure 2.5**) have been developed by the Passive House Institute:

1. **Building design:** The Passive House Planning Package (PHPP), used to asses and inform the design process or verify compliance with Passive House Standard
2. **Designer:** Certification for designers who have the skills and expertise to deliver Passive House building.
3. **Building construction:** A certification process for Passive House buildings, which applies to the completed building, Passive House retrofit and the proposed design.

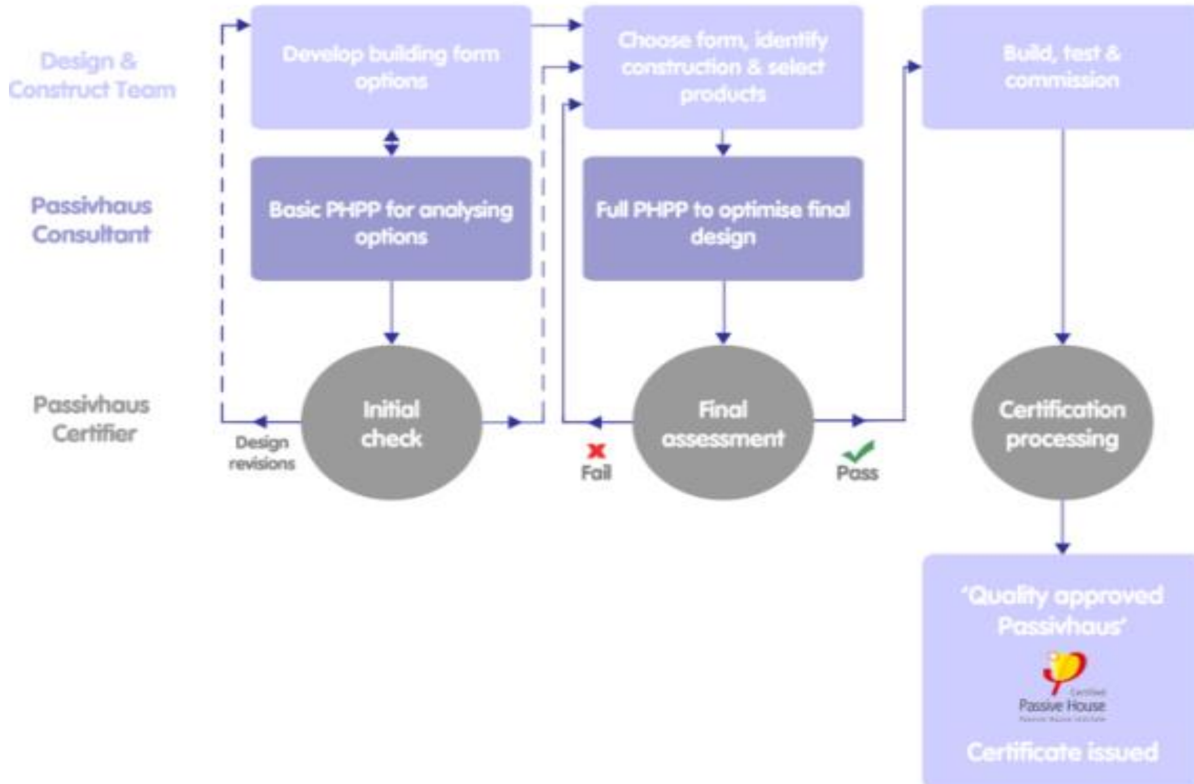

Figure 2.5 Passive house certification process (Adapted from Passive House Institute 2011)

2.8. Reasons for certifying Passive Houses

Political reason

The Energy Performance of Buildings Directive (EPBD) demands that an energy performance certificate should be available for public building display and should be readily accessible when renting or selling a house. The current passive house labels and certificates can be merged in the political sphere of the evolution of the EPBD. The development of energy efficiency design in buildings has remained the political ambition of many EU countries. The European Commission stresses in its "energy efficiency action plan" that low energy buildings such as passive house standard will be included in the future adaptations of the EPBD (EC 2008). According to Dyrbol (2008), the Passive House design as a means of reducing energy use in building sector is seen as a long term political ambition by many countries. Moreover, industry-initiated target has been initiated in many EU countries with full government support, for instance, in the UK there are a lot of mandatory standards in achieving sustainable constructions. Similarly, in France the “Grenelle de l’environnement” ensures that all new built will be zero carbon with Passive House standard by 2025 (Erwin 2014:3). In Germany, the increase in the level of energy performance of buildings is projected to nearly passive in few years’ time and the government program “Enhancing energy efficiency in building” indicates specific target for reduction in energy consumption for different types of buildings (Erwin 2014:3). In the Hanover, Frankfurt and Heidelberg regions, specific passive houses target has been projected by the transformation arena “Living building” (Erwin 2014:4).

Economic reason

Different regions and countries in EU have a wide range of financial incentives for energy efficient investments in buildings, e.g. attractive loan, subsidies and tax deductions. For Passive House, certain requirements are to be met to receive these benefits, meaning that these requirements must be confirmed by a recognized independent body of experts.

Social reason

Consumers are now becoming more conscious of their possibilities under the influence of media and information technology. According to Erwin (2014), during the initial design phase of a building, consumers’ right and will are often stated in a clear and detailed manner. Consumers are prone to “value the energy and non-energy benefits of Passive Houses” (Erwin 2014:4). Moreover, in Passive House Standard, performance-based contracting is usually initiated. The airtightness of the building envelope must be tested, and the energy performance must be calculated before the certification of the new built. The certification enables the consume to belief the authenticity of the building such as good indoor environment, thermal comfort and energy saving performance (Dyrbol 2008). However, many passive house owners are not conversant with the controls and technologies commonly used in passive house. It should be noted by the contractors' services provided are specified correctly, commissioned and installed. In addition, adequate information should be provided for the users to ensure occupants' satisfaction and correct operation. Certain groups of users such as the elderly may require additional information and pro-active engagement on the features of passive house.

Business reason

Market growth is supported by financial benefits and stimulated by producers of installations, window frames and air exchanger. Whether local, national or regional, producers can only be recognized as the market leaders when their products differ from their competitors. Passive House certification is viewed as a marketing strategy in many countries, aiming to promote energy saving performance higher than the regulated ones (Erwin 2014). Passive House Standard has been developed with benefits by companies to start an innovative and serious image. Passive house certification provides credentials for companies. For instance, many companies see certificate or a label as additional value for a system or a product. The German passive house certificate, the quality assurance label in Belgium are typical examples of where passive house certification exists for individual projects. For passive house technologies and certain passive house design strategies such as high energy efficiency windows, heat recovery systems and triple glazing, certificated are issued in Germany by a body of experts. These certificates also indicate energy related parameters of the design strategies, products and specify comfort.

2.9. State of the Art

2.9.1. Central Europe (Germany)

Since the mid-nineties, passive house standard in Germany for example has seen a rapid development. Currently, Germany has more than 6000 residential and non-residential buildings with Passive House Standard, including Passive House retrofits. The Passive House Standard is a requirement for the construction of buildings that belong to municipality in some cities in Germany, e.g. Kreis Lippe, Leipzig and Frankfurt (Erwin 2014). Moreover, the provision of a beneficial loan by the German state bank (KfW) is the major economic driver for the construction of Passive Houses and low energy buildings in the country. In 1997, Passive Houses and Passive House suitable components certification systems were introduced in Germany by the Passive House Institute, Darmstadt. The certification of the "quality proofed Passive House" is an assurance that the built complies with the Passive House Planning Package (PHPP) (Passivhaus Institut Darmstadt 2007?), and the Passive House limit values are then validated in accordance to PHPP. Furthermore, the limit values for total primary energy and total energy demand are then assessed to confirm if it fulfills the passive house requirements.

The PHPP progresses singly form the German building legislation. All the boundary conditions and procedures are independent without any special interest of stakeholders and political influence. It gives room for fast integration of results from new research. PHPP is a highly-esteemed tool in Germany because of these qualities. Many construction companies in Germany now receive certificate for passive house technologies (building systems, health recovery systems, frames, glazing, etc.) by the Passive House Institute Darmstadt (Dyrbol 2008).

2.9.2. North America (USA)

According to Florian (2018), passive house standard can work well even in the humid and warmest climate. However, adequate project planning and adapted tools are required. Passive houses have been certified to PHIUS+ in the United States to date and it is largely equivalent to the German Passive House Standard, "where cost-effectiveness is based on the calculation that higher expenditure for measures such as insulating the building is more than offset by not needing an expensive waterborne heating system and through reduced energy needs" (Florian 2018:1). However, in the United States, these savings are not readily pronounced because homes in the United States have cheaper cooling and air heating systems, moreover, the price of fossil fuels are significantly lower in the United States as compared to Europe. Nevertheless, besides high energy efficiency of Passive House, it offers other enormous benefits, for instance it can minimize the impact of daytime climate fluctuations and helps the indoor climate to stay pleasant throughout the year (Florian 2018, Erwin 2014, Dyrbol 2008). Passive House does not incur any damage even under extreme weather conditions, which might at times lead to power blackouts for days.

2.9.2.1. One piece of software for many questions

WUFI® Passive is an established building simulation software, first launch in 2012 by PHIUS and Fraunhofer IBP's Hygrothermal Building Analysis working group. The purpose of the collaboration was to develop a planning package that was adapted to the American Passive House's needs and requirements. Contrary to the moderate climate in Central Europe, the prevailing humid and warm climate in certain regions of the United States makes it necessary to dehumidify and cool the room air. In the planning phase, the software allows users to design and certify the energy layout of the building, to view the individual components and the whole building in terms of hygrothermal dynamics. This helps to ensure that the building is free from damage, that the tenants will be able to live in comfort, and that proper hygiene conditions are intact in the long run (Florian 2018).

2.9.2.2. Evolution of a climate-adapted Passive House Standard

Following the development of Fraunhofer IBP's software, the working group also helped PHIUS to establish a climate-adapted Passive House Standard (the PHIUS+ 2015 Standard), while considering various building traditions in the United States. It was almost impossible to apply energy-efficiency building design that is cost effective in many regions of the United States, which led to the construction of buildings without adequate level of comfort in some cases. The standard hardly gain acceptance as a result. In response, the working group sought to come up with a standard that accomplished ambitious reduction in energy use and emissions of $C0_2$, but were also cost effective. To achieve this, climate-dependent limit values were calculated for more than a hundred locations, encompassing aspects such as cooling requirements and the annual cooling and heating requirements or the peak cooling and heating loads (Florian 2018). Then the techniques were integrated into WUFI® Passive. As a result, Fraunhofer IBP's software has remained the standard tool for certification and design of passive houses in the United States.

2.9.3. Australasia/South Pacific

For the past 24 years, Passive Houses have been around internationally, however, in Australia the first accredited Passive House was completed in 2014. According to Susan (2015), the mechanical ventilation with heat recovery (MVHR) system of Passive House Standard provides remarkable indoor air quality in passive house buildings. For instance, in Australia, increase in air tightness leads to an increased risk of poor indoor air quality and condensation. Moreover, this is a common phenomenon in North America and in Europe, but they were able to overcome these challenges by developing methodologies that prevent thermal bridges and systems to ensure healthy buildings.

Increasingly, Passive House designers in Australia are solving these challenges by improving on detailing and material specification, to reduce thermal bridges and avoid condensation.

To paraphrase Martin (2015), improved indoor air quality may help to manage high prevalence of allergies and asthma in Australia. Controlling allergies and asthma by Pre-cooled and Pre-heated filtered fresh air of Passive Houses technologies is an added benefit of thermal comfort and energy efficiency design strategies of Passive House Standard Martin (2015), Susan 2015). Conventional Heating, Ventilation, and Air Conditional (HVAC) systems take in a certain amount of fresh air which then needs to be cooled or heated to a temperature that is comfortable. Without any cross-contamination, the mechanical ventilation with heat recovery system cools the incoming air and enables the outgoing air to warm. Depending on the effectiveness of the heat exchanger, more than 90% of the heat coming from the exhaust air can be transferred to the intake air, bringing the incoming air almost up or down to room temperature (Susan 2015).

In houses with low-permeability, it is essential to control ventilation. Heat from the used, stale air is recovered and transferred to the incoming air by the mechanical ventilation with heat recovery system of Passive House, resulting to reduced $C0_2$ emission and energy use (Martin 2015). The mechanical ventilation with heat recovery systems have strict criteria to meet Passive House standards. To ensure fresh air inlet into the air tight building, the high energy efficient MVHR system works all day. Moreover, to ensure energy efficiency, the windows should be closed while the system is operating. Depending on the MVHR system and the design strategies of the building, in a moderate outdoor temperature, the system can be switch off to open doors and windows for natural ventilation. As Susan (2015), Martin (2015) put it, many at times in Australia, the outdoor temperatures are comfortable. Therefore, building Passive Houses to work in 'natural ventilation' mode as well as in 'mechanical' mode is a pertinent design technique.

2.9.4. China

The Passive House concept has attained yet another remarkable milestone in the growing market of China. The country's first residential building designed to this highly efficient standard has been certified in the city of Zhuzhou, China. Although, the energy efficiency design strategies were closely supervised with professionals from Europe, the building was mainly developed by Chinese stakeholders using local materials. This shows the extent at which Chinese industrial sector has adapted itself successfully to the construction based on Passive House Standard. Typically, in China, the operation of buildings accounts for more than a third of the total energy consumed, with the Passive House technology, this consumption can be reduced by some 90% (Passive House Institute China 2018). Other than China, no other country is seeing more new construction in the world. Therefore, it is paramount that the trend is moving towards energy efficiency and greater sustainability for the protection of the global climate.

2.9.5. United Kingdom

As at 2008, there are no dwellings in the United Kingdoms that meet the Passive House Standard, however, many projects were at the planning phase. Many clients, specifiers, architects, manufacturers and regulators noted that testing and third-party certification can be the only justifiable way of demonstrating compliance with standards and other criteria (Erwin 2008), Building Research Establishment Ltd. Was established as a result, authorized by the Passive House Institute in Darmstadt to certify buildings that are built to Passive House Standard in the U.K. Reaching certification in the U.K. is subject to the same criteria as in Germany, however, little differences still exist. For instance, due to the milder climate in the U.K, the criteria for air tightness is set less strict, equal to one volume air change rate per hour under 50 Pascal pressures. Moreover, confirmation of correct commissioning of the mechanical ventilation unit and airtightness testing is required. For good indoor air quality, the use of paints with minimal amount of volatile organic compound (VOC) is recommended. After meeting all the requirements and successful certification, the owner of the building can then be eligible for reduced rated “Green” mortgages. Before Energy Performance Certificate is given, the Building regulations in the U.K. demands the calculation of Standard Assessment Procedure Energy. Therefore, PHPP calculation is used to demonstrate compliance of new built with the Passive House Standard. In the U.K. the Passive House concepts are recognized as a major pathway for reaching higher levels of the Code for Sustainable Homes and building regulations (Erwin 2008, Lars 2018).

2.9.6. Ireland

Passive House Association of Ireland was established in 2010 by a group of enthusiastic professionals, with the aim to educate, promote, facilitate and to develop a strong identity and to create a demand for the concepts of Passive House Standard in the country. The Association has ever since been active in Ireland and across Northern Ireland. Until now, approximately 310 Passive Houses have been certified in the country, resulting from the relatively mild Irish climate which offers a suitable condition for the application of Passive House concepts. Dwelling Energy Assessment Procedure (DEAP) is the method used by Irish officials for rating and calculation of energy performance. The use of DEAP for calculating Passive House dwelling will result in ‘A2/A3 to B1’ grading (Lars 2018, Passive House Association Ireland 2015). Moreover, the calculation of specific heat requirements in DEAP is quite like PHPP calculation, although some differences exist for calculating primary energy. For instance, household electrical gadgets are not included in DEAP calculation while PHPP calculation requires household appliances.

2.10. Concluding remarks

The concept of passive design in buildings has evolved over the last 15 years, however, achieving Passive Standards in cold climate of Northern Europe is different from achieving it in Middle East where mechanical cooling is necessary to achieve optimal level of cooling and occupant comfort. Whereas, in tropical climate, buildings are naturally ventilated and end up consuming significantly less energy, which gives occupants the feeling that they are closer to nature.

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3.0. Indoor Environmental Quality in Passive House Standard

In this chapter, I will describe how thermal climate in the indoor environment affects human body. Furthermore, how human body is affected by thermal comfort, how thermal comfort is described in standard and measured by Fanger's indices[1]. This chapter provides an overview of the body of knowledge on Passive House technologies and indoor environmental quality; comparing and evaluating previous studies relating to indoor environmental quality in modern, airtight Passive House dwellings.

3.1. Thermal climate

Even though human body is exposed to different thermal climates, it tries to maintain a constant body temperature of 37^{0}C by automatic mechanisms in the body, e.g. sweating, increased blood flow and by human behaviour. When the body is affected due to temperature changes, the automatic mechanisms will operate by sweat, blood flow and body muscles which will regulate the body temperature. Seeking shadow, opening windows, decreasing or increasing the number of clothing, regulating the level of activities are the examples of human behaviour that is regulating the body temperature.

Different people experienced thermal climate differently and there are different factors that influenced how the surrounding thermal environment is perceived. Human heat balance is affected by the following environmental factors:

- Air temperature
- Air velocity
- Relative humidity

[1] Fanger's indices is founded on heat balance models and thermoregulation. According to these models, the human body employs physiological processes (e.g. shivering, sweating, regulating blood flow to the skin) to maintain a state of equilibrium between the heat produced by metabolism and the heat lost from the body.

- Radiant temperature

Heat exchange between the external environment (surrounding) and the body is influenced by the above-mentioned factors. For instance, the convection losses from the surface of the skin is affected by air temperature since the surrounding air is heated by the body. The body heat balance is directly affected by the radiant temperature. The evaporating of sweat to the air depend on the relative humidity. In other words, the relative humidity is inversely proportional to the volume of sweat that is evaporated into the air (body evaporates more volume of sweat into the air at lower relative humidity and vice versa), both evaporation and convection are affected by air velocity. Exchange of surrounding air is affected by increased air velocity, evaporation and convention (Gavhed et al., 2006). Other than the factors described above, thermal climate can also be influenced by individual factors, e.g. activity level and clothing. The degree of clothing and its insulating ability is measured in clo, starting from 0 to 2.2. The minimum clo of 0 is naked while the maximum 2.2 is outdoor winter clothing and 1 clo is underwear. 1 clo is equal to $0.155 m^2 K/W$, and it is the amount of insulation required by a person at rest to maintain normal airflow and heat balance in an environment at 21˚C, while metabolic energy production [met] is used to measure activity level. For instance, 1 met equals to an average person at rest with the energy production of 58 W/m^2, the area refers to surface area for human body. According to ASHRAE standard 55, for an average person, the surface area is around 1.8 m^2 (Jimmefors 2014).

3.2. Thermal comfort

The condition that expresses satisfaction or a state of mind when a person feels comfortable with the thermal environment is known as thermal comfort (ANSI/ASHRAE Standard 55). However, due to individual differences, people generally derived satisfaction at different thermal environment. Predicted Mean Vote (PMV-index) is used to determine indoor thermal climate. This index predicts the average response of human population, with clothing and activity level, measured by thermal sensation scale. The seven-graded scale starts from -3 to +3, where 0 is neutral sensation, +3 is hot and -3 is cold. According to the European standard EN ISO 7730:2005, the comfort zone is between -0.5 and +0.5.

The PPD-index index can then be calculate having known the PMV-index of the Predicted Percentage of Dissatisfied people. The reaction of the individuals at a certain thermal condition can be measured quantitatively by the PPD-index, and more also the PPD-index is used mostly to determine the thermal environments by investigating the thermal comfort. The PPD-index ranges from 5% - 75% (see figure 3.1), as stated by EN ISO 7730:2005, the index should be used only for PMV values between -2 and +2. The 5% is the lowest number of dissatisfied individuals and, it exists because the difference in people’s opinion regarding thermal comfort is inevitable.

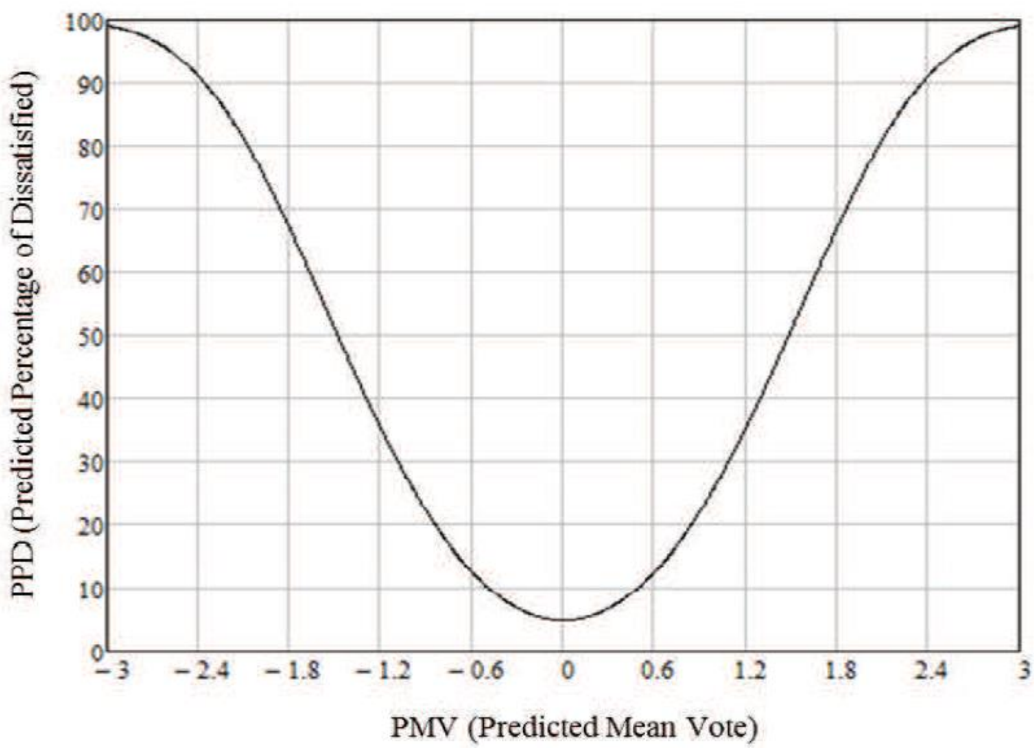

figure 3.1. Correlation between PPD of Dissatisfied individual as a function of the PMV (Jimmefors 2014)

Evaluation of thermal comfort is usually done with a Predicted Percentage Dissatisfied index (PPD-index). PPD-index considers differences within a large group of people. It determines the statistical percentage of a population experiencing discomfort at certain thermal conditions. Moreover, since individuals have different optimum thermal comfort, the minimum number of dissatisfied people at any given thermal condition is 5%.

3.3. Thermal Comfort in Passive Houses

In Passive houses, the thermal environment is completely different from that in conventional houses. The reason being that the transmission losses, thermal bridges and air leakages are lower through the building envelope in Passive house standard, hence thermal comfort is achieved with lower need of supplied energy (Feist 2006, Giovanardi et al., 2009). However, between spring and summer, the indoor temperature often increases due to additional heat from the solar radiation, therefore Turunen et al., (2016) argue that to reach a comfortable indoor temperature during these seasons, it is crucial to air Passive houses. Moreover, "in winter, there is a higher heating demand that the internal heat loads are unable to fulfil" (Turunen et at., 2016:14). Heat exchanger such as radiators are often used in conventional buildings while the Passive houses such as those in Hungary are heated by the supply air. In general, different people have different desired indoor temperature and the desire varies with seasons. For instance, the desired indoor temperature during the warm season of the year are higher than in winter.

3.4. Daylight

Daylight comfort is another parameter for indoor climate. Löfberg (1987) recommends that, adequate level of daylight can be accomplished in a building if the window glass area is about 10% of the floor area. The level of indoor daylight is determined by the daylight factor (DF). Daylight Factor is aptly defined by Jimmefors (2014) as the correlation between the external and internal illuminance. At the point of interest, the illuminance is calculated as the sum of externally reflected light (ERC), internally reflected light (IRC) and direct light from the sky (SC). IRC is the contribution of the reflection that appears indoors, while the major component of ERC is the reflected light on vertical surfaces outside the room which screens the sky (Jimmefors 2014).

3.5. Energy efficient design and Indoor Air Quality

Scholars such as Bas (2004) and McGill (2016) have shown that indoor air contains higher level of pollutants in industrialized countries than ambient air, yet literature on air quality particularly focus on ambient conditions. Indoor air contains different types of pollutants that can pose major health risks, according to Anderson et al., (2004) and McGill (2016), despite the enormous number of indoor air pollutants, only a few of them have been properly categorized (Table 3.1). For example, Brooks (1991), Davis (1991) argue that indoor air could contain up to 900 different pollutants, and that includes various gases, water vapour and particles in every air we breathe (McGill 2016, McCarthy & Samet 2001).

Table 3.1 Indoor environmental quality guideline from WHO and EU (adapted from Ulla et al., 2016)

Parameter	Unit	WHO	EU
Tc	°C	-	-
Tw	°C	-	-
RHc	%	-	-
RHw	%	-	-
CO_2	ppm	-	-
CO [4]	ppm	8.6 (8h); 25 (1h)	10 (8h)
$PM_{2.5}$	μg/m^3	25 (24 hr)	25 (yr)
PM_{10}	μg/m^3	50 (24 hr)	50 (24 hr); 40 (yr)
NO_2	μg/m^3	40 (yr); 200 (hr)	200 (hr); 40 (yr)
Formaldehyde	μg/m^3	100 (30 min)	-
Radon	Bq/m^3	100 (yr)	-
TVOCs	μg/m^3	-	-

To paraphrase Gurjar (2010), Ojha & Molinahe (2010), quality of indoor air is known by its chemical, biological and physical features. The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) defined acceptable Indoor Air Quality as

> *"Air in which there are no contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (*ASHRAE 2013:3).

The definition stresses the importance of both comfort and health requirements, however, the posit that indoor air is acceptable if substantial majority or 80% of the exposed group are not dissatisfied may not be regarded as an adequate metric for houses with low occupancy levels such as dwellings. Similarly, Doty (2007), Turner (2007) aptly define acceptable indoor air quality as air in which the level of contaminants is maintained below the concentration that could cause discomfort, allergic reactions, illness or the absence of pollutants that may hinder the comfort or health and well-being of building occupants (Rousseau et al., 2003). The quality of indoor air goes beyond the composition of specific gases, particles and chemicals. Indoor air pollutants are estimated at 900 with potential to impair health (Davis 1991, Hanke et al., 2007, McGill 2016). Moreover, according to Bluyssen (2009), indoor chemistry creates several hundreds of new chemicals of which their constituents are unknown. Inadequate knowledge of these components can result in erroneous speculations of quality. Apparently, with the speedy introduction of present-day technologies and new materials with unknown adverse effects, we may not fully understand the effects of every indoor pollutants. Indoor air quality can be objective and subjective, quantitative and qualitative, measured and perceived (Doty 2007, Turner 2007). Hence, evaluation of indoor air quality should embrace a more holistic approach including the physical, psychological and social impact of indoor air quality on building occupants and should not only be limited to physical make-up.

3.6. Fresh versus Sterile air

According to Krainer (2008), fresh countryside air is composed of over three hundred and fifty million different suspended substances. Furthermore, Spengler and Samet (1991) suggest that ambient air consists of different suspended particles, ranging from natural to anthropogenic origin such as seeds and spores, natural gases, bio-effluents by living organisms, biological production of fibres, suspension of particles through wind and wave action. Except in certain circumstances, e.g. hospitals, sterile air that is completely devoid of natural substances has the potency to cause damaging effects to health (McGill 2016). Many scholarly articles such as those written by Mori & Scearce (2011) shows that sterilized environment may impair human ability to build healthy immunity against infections. For example, a study by Plat-Mills (2002) shows that the prevalence of allergy related diseases is low among children that exposed to pets and livestock. This claim is also supported by McGill (2016) who argues that increasing separation from the natural environment and improvements in human living conditions may eventually result to lack of basic environmental cues that help the body to regulate immune system. Studies such as Sundell (2004) have traced numerous building related symptoms including allergies and dermatitis, asthma, multiple chemical sensitivity and sick building syndromes to increased exposure to indoor air pollutants. According to Raw (1995), Hamilton (1995), health effects range from physiological alterations, irritation, acute and chronic illness to sudden death. Therefore, it is recommended that the improvement of indoor air quality should be done concurrently with the improvement of ambient air.

Over the years, there has been a swift rise in the use of air filtering, purifying and cleaning technologies, triggered by an increased awareness of indoor air pollution (Chivian et al., 2002). Most of these technologies help to reduce the concentration of indoor air pollutants and effectively filter dangerous microbes and their toxins in indoor air. However, it is known that the air filtering technologies can reduce levels of natural particles and beneficial bacteria that are inherently present in the air. Different human activities often obstruct the structure and function of ecosystems that support life, resulting into severe health issues now and for the future generations (Chivian et al., 2002). As human depends directly or indirectly on nature for survival, any obstruction of natural process may have adverse effects on human health.

3.7. Automation and technological devices versus user control

The treacherous dislocation from the natural environment is a result of damaging effects of technological advancements and global consumerism. To paraphrase McGill (2016), the propensity of technology to integrate interior conditions leads to sensory improvement. Houses have lost their depth and capacity, discovery, misery, sensory invitation, and shadow (Pallasmaa 2000). Studies have shown that occupants in buildings with complicated technological gadgets for environmental control and regulations generally have series of complaints (McGill 2016, Kurvers 2006). According to the study carried out by Manchanda (2010), Steemers (2010), the study investigates twelve office buildings and the results show that there is a positive correlation between increased mechanization, increased energy consumption and reduced tenant control, resulting into reduced tenants comfort and satisfaction. In a more technical building, tenants require more knowledge and understanding to maintain and operate them properly. According to Kurvers (2006), Leyren (2006), provision of adequate air supply by mechanical ventilation may degenerate the indoor climate due to inadequate maintenance, tenants lack of understanding and increased potential for failures. Clausen (2003) further explains the potential risk associated with technical failure in the statement below:

> *"Buildings tend to get technically more complicated and require more skillful labour to operate them. Unfortunately, the building operators are not always trained properly to*

perform their tasks, which may lead to poor operation of the building and a deteriorated indoor climate" (Clausen 2003:71).

Moreover, studies by Leaman, Bromley and Bordass (1993) show that over dependence on mechanical ventilation systems in houses does not provide the expected results because of indoor air quality problems, presence of sick building syndromes, lack of integration, lack of proper hygiene and tenants discomfort. Yet, technological gadgets are predominant in many modern sustainable buildings and occupants are deprived of the choice and having their control replaced, e.g. opening windows with computer controlled and automatic systems (Kumar, Mahdavi 1996).

3.8. Advanced ventilation

To ensure adequate indoor air quality, it is paramount to have prerequisites for ventilation. For instance, as required by the LEED for Homes rating system, the ventilation and design of intermittent ventilation, continuous ventilation, passive ventilation and whole-house ventilation systems to ASHRAE standard 62.2-2007. However, this section intends to 'minimize tenants' exposure to indoor contaminants by ventilating with outdoor air' (McGill 2016:63, USGB 2010:90) which concludes outdoor air is fresh, whereas, it is usually not the case in every condition. For the use of energy and heat recovery system, two credits are given to foster the recovery of energy and heat lost via ventilated air. However, for third-party performance testing, a credit is given. McGill (2016) argues that performance testing is equally important and should be given two credits accordingly, particularly in mechanical ventilated homes such as Passive houses where actual ventilation may widely differ from designed ventilation. The entire house ventilation system or even a heat recovery system may not be able to meet criteria for ventilation, hence, appropriate post-occupancy survey is crucial.

In the context of Passive house standard as explained in Table 3.1, "reference to IAQ is limited in the PHPP to a required average minimum air change rate (ACR) of 0.3 h^{-1}" (McGill 2016:63). Research indicates that ventilation air change rates below European standard of 0.5 have been linked with mold growth, allergies, perception of poor indoor air (Wargocki et al. 2002, Engvall, Wickman & Norbäck 2005, Dimitroulopoulou 2012) and settled house dust (Bornehag, Sundell & Sigsgaard 2004, Bornehag et al. 2005, Ucci et al. 2004).

Table 3.1 Credits for advanced ventilation (McGill 2016)

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- CO_2 or alternative air quality sensors required with warning signals and/or linked to ventilation system.	1	No
Passive house: Average Minimum Air Change Rate (ACR) of 0.3 h−1		n/a	Yes

3.9. Air filtering

Studies have shown that suspended particulate matter produced by household cleaning, tobacco smoking, cooking and combustion can impair human health, particularly respiratory and cardiovascular system (Lindvall & Seifert, Maroni 1995). In order to reduce suspended particulate matter from the air supply system, LEED recommends the use of filters with a minimum efficiency reporting value (MERV) of 8 (USGBC 2010), with '1 credit awarded for a MERV of 10 or more, and 2 credits awarded for a MERV of 13 or more' (McGill 2016:63). As indicated in Table 3.2, the level of protection from suspended particulate matter with the average size of 3 and 10 μm provided by the filters with MERV of is greater than 70%; however, it may not be efficient to filter particles ranging between 0.3-3 μm. As Yassi et al., (2001) aptly put it, suspended particulate matter with smaller diameter such as ultrafine (<0.1 μm) and fine (<2.5 μm) can cause serious health issues due to their ability to go deep into the lungs and deposit in alveoli or air spaces of lower respiratory tract. In relation to the Passive house standard, minimum filter grade of F7 is required for the fresh air intake, which is equal to an MERV level 13. According to McGill (2016:63), this 'filter grade provides an efficiency of 90% for particles sized 1–10 μm in diameter, but only 75% efficiency for particles between 0.3 and 1 μm'. No credits are awarded for the use of filters by the BREEAM Eco-Homes, Code for Sustainable Homes and BREEAM Multiresidential, hence, the significance of filter efficiency in mechanical ventilated systems is not properly addressed. EPA (2003) suggests that particles with the diameter less than 10 μm may easily slip through the lower respiratory tract and enter the bloodstream, therefore, it is paramount to protect occupants from the inhalation of suspended particulates, most especially in highly polluted areas. Moreover, occupants should be fully aware that filter grade of F7 with higher MERV ratings should be cleaned regularly or replaced to ensure adequate performance.

Table 3.2 MERV Comparison 2011 (adapted from Hansen and Burroughs 2012)

EU ratings	MERV level	Original Dust Spot %	% 0.3-1µm	% 1-3µm	% 3-10µm	Typical Particulate Filter Type
G1, G2	1	NA	Too low efficiency to be applicable to 52.2 determination			Low efficiency fiberglass and synthetic media disposable panels, cleanable filters, and electrostatic charged media panels
	2	NA				
	3	NA				
	4	NA				
G3	5	NA			20-35	Pleated filters, cartridge/cube filters, and disposable multi-density synthetic link panels
G4	6	NA			36-50	
G4	7	25-30%			50-70	
F5	8	30-35%			>70	
F5	9	40-45%		>50	>85	Enhanced media pleated filters, bag filters of either fiberglass or synthetic media, rigid box filters using lofted or paper media
F6	10	50-55%		50-65	>85	
F6	11	60-65%		65-80	>85	
F6	12	70-75%		>80	>90	
F7	13	80-85%	>75	>90	>90	Bag filters, rigid box filters, minipleat cartridge filters
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	99.97% IEST Type A			HEPA/ULPA filters evaluated using IEST MoT. Types A through to D yield efficiencies @ .3µm and Type F @0.1 µm
	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			

3.10. Radon protection

Radon is a well-established lung carcinogen present in the indoor air, is a chemically inert radioactive gas and formed from the decay chain of uranium (Darby et al., 2001, McCarthy & Samet, Spengler 2001, Gunby et al., 1993, Bone et al., 2010). It is argued *that*

> *"energy-efficient strategies such as the installation of draft proofing and double glazing may potentially increase radon indoors levels by more than 50%"* (McGill 2016: 72).

However, the only assessment scheme addressing this concern is LEED, and the reduction of radon exposure is done by the using radon-resistance construction method as recommended by the EPA, International Residential Code, Indoor Air Quality Code and Washington State Ventilation (USGBC

2010). According to LEED, ‘radon-resistant construction does not guarantee that occupants will not be exposed to radon’ (USGBC 2010:97), hence, to determine the degree of exposure, EPA recommends radon test for all homes and this should be incorporated in LEED rating criteria, so the performance of radon-resistant construction design strategies can be achieved in practice.

3.11. Dependence on mechanical ventilation systems

Due to technological advancements and crave for reducing energy use, MVHR systems are now practically standard in Passive House Standard. According to Mardiana-Idayu (2012), these systems have been found to accomplish energy saving performance in buildings (Mlecnik et al., 2012), improved thermal comfort (Schneider 2006) and improved indoor air quality (Richardson 2011). However, several studies have also noted numerous challenges with MVHR, such as lack of maintenance (Gill et al., 2010), poor installation (Sullivan et al. 2012), lack of awareness and knowledge of the systems by the users (Bone et al. 2010), noise and thermal comfort complaints (Balvers et al. 2012).

Similarly, a review by Gupta (2013) has helped to provide some insight into concerns associated with the quality of MVHR from German context. Parallel to the findings from UK studies, they highlighted a few issues with the delivery of ventilation systems from the local market, including lack of practical guidelines for maintenance and installation and standard compliance requirements. In the study, two monitoring projects were presented in Germany (CLEAN AIR FLOW ENERGY and OPTIVENT), all outlined health problems with insufficient air exchange rates in houses with MVHR. However, there are also naturally ventilated houses with more complaints of building related health symptoms than in some mechanically ventilated dwellings (Hodgson 2002). There is no direct link between indoor air exchange rates and building related health symptoms, moreover, it is not reported that increase in fresh air supply will eliminate health symptoms in dwellings.

3.12. Sick building syndrome (SBS)

SBS is a group of building related heath symptoms that are caused by indoor climate of a dwelling (Arif et al., 2016, Brager 2002). Furthermore, SBS is exacerbated by closure of natural openings and use of new construction materials which are not certified or adequately tested and closure of natural openings (Helmis 2004, Simonson et al., 2002, WHO 1993). Uncomfortable humidity and temperature, biological and chemical pollution, psychosocial status and physical condition are some of the factors leading to SBS (Arif et al., 2016). Irritation of the eyes, throat and nose, headache, light sensitivity, cognitive disturbance, cough, depression, other flu like symptoms and gastrointestinal distress are some of the symptoms experienced by people with SBS (Simonson et al., 2002, Wang et al., 2007). According to Takigawa et al., (2009), Redd (2002), coupled with ventilation, there are other related SBS risk factors such as allergens, volatile organic compound, mite, dust, lighting, indoor aldehydes, carbon dioxide, air exchange rates and carbon monoxide.

Studies have shown that hypersensitivity pneumonitis and asthma were linked with inflammation and atopy triggered by exposure to biological contaminants in indoor air (Arif 2016, Redd 2002). Findings from the studies conducted in the United States on indoor climate reveal that microbial load in chair dust or floor lead to asthma, eye irritation and upper respiratory illness (Apostolakos et al., 2001, Boulet et al., 1997, Dharmage et al., 2002). Based on these findings, it is paramount that buildings should be designed in such a way that it will limit exposure to indoor pollutants, continuous control and monitoring of indoor air, and wet areas should be ensured. Selection of suitable, third party certified building materials is of great importance to ensure good indoor climate and reduction in SBS.

3.13. Microbial contamination

The WHO (2009) has revealed that there is a positive correlation between exposure to microbial pollutants due to excessive indoor mixture and diseases of public health importance, including allergies, asthma, immunological reaction and acute respiratory infections. Settled dust mite and fungal growth is reduced by reducing the levels of relative humidity, however, low levels of relative humidity are also known to impair health, leading to many health symptoms such as common colds, increased discomfort and irritation of mucous membrane (Hansen & Burroughs 2004). Moreover, criteria for microbial pollution has been developed by BREEAM Multi-Residential scheme, however, the criteria are restricted only to the prevention of Legionnaires infection. Microbial pollution should encompass issues such as airborne bacteria and mold. Strategies to prevent mold growth should be addresses and awarded appropriately. Most importantly in air-tight buildings such as Passive houses, where the risk of high moisture level is evident due to reduced infiltration, house dust mite and mold could thrive and eventually predispose occupants to risk of acute respiratory infections (McGill 2016, Quansah et al., 2012). However, in order to avoid settled dust, moisture and mold growth in Passive Houses, mechanical ventilation with continual aeration is ensued, including good thermal protection (Nicol, Humphreys & Roaf 2012).

3.14. Indoor air Quality and health

The Environmental Protection Agency (EPA) classified air pollution as one of the major environmental risk factors to human health (EPA 2013). However, exposure to indoor air pollutants does not usually produce immediate health effects (NIOSH, EPA 1991). For example, according to Jones (1999) and Seltzer (1997), the risk of air pollution related symptoms depends on the concentration of pollutants, current state of individual's psychological and physical health, individual's susceptibility, duration and frequency of exposure. Similarly, it is often difficult to diagnose indoor air quality related symptoms because many illnesses are nonspecific and can be associated solely with stress or in combination with other risk factors (Colome et al., 1994). Moreover, this study does not intend to present exhaustive review on indoor air pollutants[2].

3.15. Concluding remarks

The Passive House indoor temperature and ventilation characteristics are considered as most crucial pathways related to occupants' health and environmental exposure, such as indoor air quality and thermal comfort. For example, the concept to improve energy efficiency using MVHR is known to reduced exposure to indoor air pollutants. However, if the ventilation systems are not regularly cleaned and adequately maintained, it is likely to become important sources of indoor air pollutants. The following chapter moves on to describe the study methodology, data collection methods, ethical implications and study limitations.

[2] For detailed information or a review of the available guideline and standards, please refer to the following reports by the World Health Organisation (WHO 2000, 2006, 2009, 2010), and books by Burroughs and Hansen (2004), Maroni et al., (1995), Spengler et al., (2001). Please see ASHRAE (2013a, 2009) and CIBSE (2001) for useful guidance documents on indoor air pollutants in homes.

4.0. Methodology

This study focused on residential Passive Houses on regional context. For this reason, findings are applicable to Australia/South Pacific, Germany, UK and Ireland, USA, China and Canada. The study considered the relationship between perceived occupants' health and energy efficient design strategies of Passive House Standard, providing an in-depth and a comprehensive reflection of the research problem. However, a detailed study of the thermal comfort and indoor environmental quality was not possible, since the quality of indoor environment cannot be based only on perception.

This research project has used mixed-methods technique:

1. Net-based post-occupancy survey questionnaire with open and closed questions
2. Occupants and household interviewer-administered questionnaire (face to face)
3. Semi-structured interview with Passive House stakeholders (Architects, Passive House Association and Certifying body).

4.1. Mixed-methods techniques

This study considers mixed method approach appropriate and most fitting for the research project, combining both quantitative and qualitative techniques, via, "multiple perspectives, viewpoints, standpoints and positions" (Woodside 2010:113). This is supported by Johnson et al., (2007:9) who says that,

> *"The use of both qualitative and quantitative techniques together to study the topic can be very powerful to gain insights and results, to assist in making inference and in drawing conclusions".*

4.2. Post-occupancy survey (net-based questionnaire)

This study was conducted as a mixed-methods design, utilizing some complementary interviews with a standardized post-occupancy questionnaire (see Appendix A) that included a series of fixed response questions about occupant's perception of indoor air quality, their knowledge of ventilation strategies and related health symptoms, as well as a series of open-ended questions where occupants were asked to self-evaluate their current state of health as compared to when living in their previous dwelling. Certain building related symptoms were used as health indicator and only the symptoms connected to the indoor air and thermal environment were taken into consideration. The questionnaire also assessed the prevalence of their previous allergic diseases compared to while living in the passive houses, and the functionality of the indoor environments were included in the survey. Questions were arranged around sub-topics, which helped to provide a logical flow to the survey questionnaire.

The survey questionnaire has subsections such as physical, chemical and biological conditions of indoor climate (noise, perceived air quality, air temperature, visible mold growth), prevalence of symptoms among occupants if any, medical history of allergic diseases, disturbing environmental factors and background information, e.g. respondent's smoking status, number of occupants in the building, age and gender.

Different standardized methods are frequently used in the literature, for instance the RIOPA questionnaires which are mostly used in the Scandinavian countries and the RSH questionnaire in the UK, issued by the Building Research Establishment, with office environments as major focus. In 1986 at the Department of Occupational and Environmental Medicine, Orebro University, the first edition of this survey questionnaire was developed (Berry et al., 1996). It has been validated since then as a reliable tool for post occupancy survey including symptoms related to indoor environment (Engvall et al., 2004, Raw 1996) and has been widely used in several studies. Alongside other sources (figure 4.1), this study used the RIOPA survey as a post-occupancy evaluation with the certified passive house occupants as the target population. Moreover, for this study, some modifications were made to the RIOPA survey questionnaire, by shortening the questionnaire for example. The final survey comprised of 23 questions related to the house, indoor environment and the prevalence of building related symptoms. Two questions were addressed on the indoor climate of their work place.

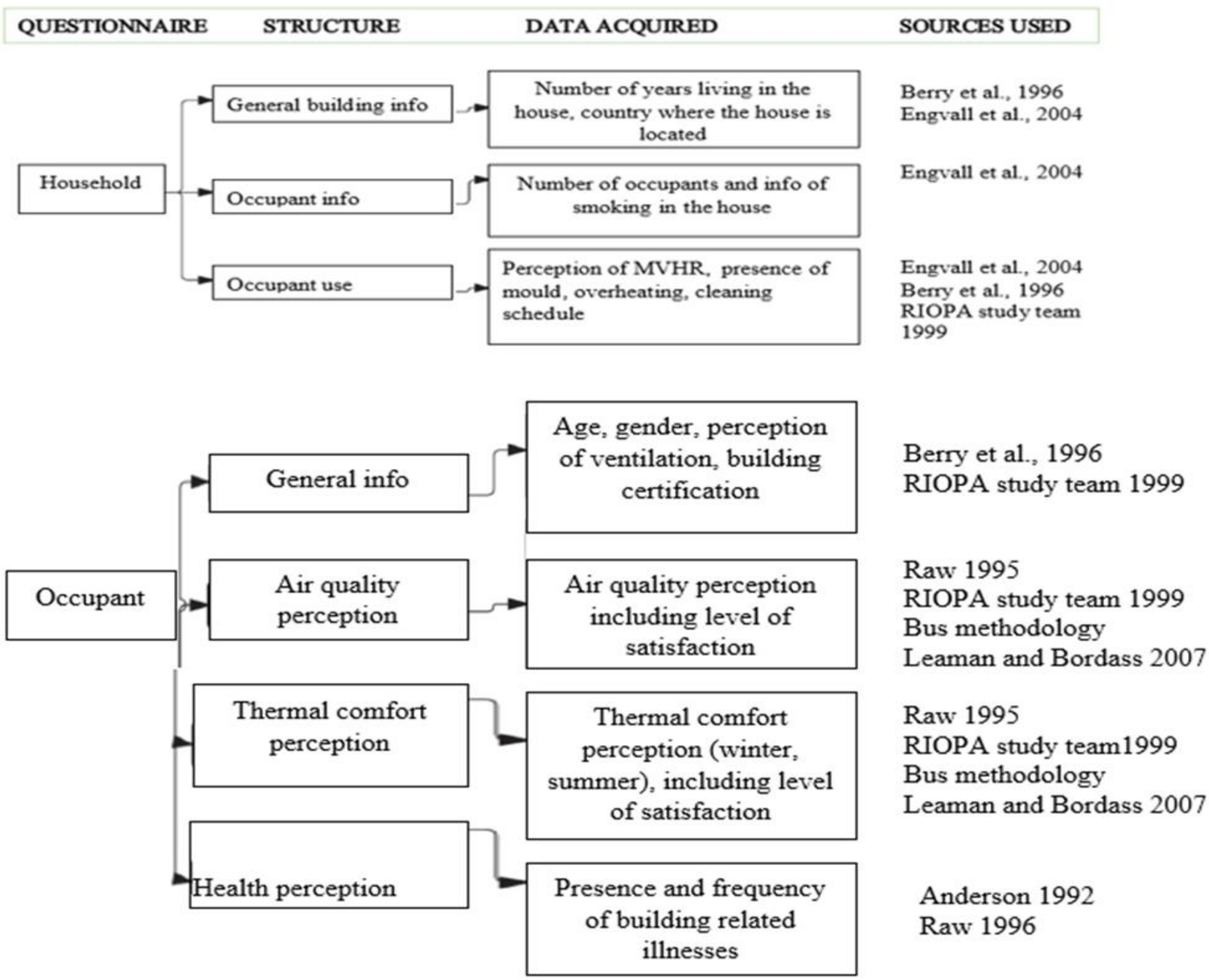

Figure 4.1 Questionnaire design and structure

4.2.1. Requirements

Occupants of well-built, certified and well maintained (cleaning schedule) Passive Houses in Australia/South Pacific, Germany, UK and Ireland, USA, China and Canada were surveyed. Primary requirements were properly built and well maintained Passive Houses. Also, occupants of Passive house retrofit were included. Recruited houses were selected from volunteering tenants, who did not receive any monetary compensation for their participation.

4.2.2. Procedure

We conducted an online survey for a convenience sample of occupants of Passive Houses across 6 countries; Australia/South Pacific, Germany, UK and Ireland, USA, China and Canada to improve responses. Several Passive House Organizations and support groups agreed to send invitations with the link to the survey to listserv members and to post invitations on their websites. The survey was accessible through Qualtrics, a secure web-based survey data collection system. The survey took approximately 15-20 minutes to complete, on average and was open from May 10, 2018 to June 8, 2018. The survey contains information about the purpose of the study, the nature of the questions and consent for instance, the survey was voluntary, respondent could skip any questions or quit at any time, potential response would be anonymous. The net-based questionnaire which gained information on perceptions of the quality of the indoor environment and health was completed by each adult in the household.

4.2.3. Self-rated health

Self-rated health status was evaluated by asking occupants: “In general, how would you rate your health and that of your household with the possible options being “very good (1), “good” (2), “moderate (3), “bad” (4), or “very bad” (5). This scale is analogous to the 5-point Likert scale of self-rated health conditions, which is a potent predictor of frequency of health symptoms, mortality, and strongly relates with other building-related health symptoms.

4.3. Interviewer-administered questionnaire (face to face)

Interviewer-administered questionnaire were completed with several stakeholders (occupants, architects, Passive House certifiers), together with open-ended questions to explore occupants' perceptions about indoor climate of Passive Houses and its effects on their health. Typically, interviewer-administered questionnaire has been used in many indoor climate researches to gather information on Building Related Illnesses, Sick Building Syndrome, Perception of thermal comfort and indoor air quality (Bowling 2005). The interviewer-questionnaire method thus enabled the use of validated and standardized procedures for the identification of building related symptoms and perceptions of the indoor climate. Administration of the questionnaire through a face-to-face interview format with stakeholders creates an avenue to clarify questions and opportunity to verify responses from the net based post-occupancy survey. For instance, results were verified by reiterating answers to stakeholders while writing them down. Questions were readdressed if contradictory answers were given. The study used a mixed-methods design, combining net-based occupancy survey with interviewer-administered questionnaire to provide quantifiable results (Kendall 2007), increase response rate and much more to limit opportunities for subjective bias. According to Bowling (2005:282), this method can,

> "*increase response and item response rates, maintain motivation with longer questionnaires, probe for responses, clarify ambiguous questions, use memory jogging techniques for aiding recall of events and behaviour and control the order of the questions.*"

Furthermore, the method could be defined as a form of semi-structured interview; using aspects of both structured (designated by utilizing questionnaire (Britten 1995)) and unstructured interview formats. As Merriam (2009:90) aptly puts it,

> *"In this type of interview either all the questions are more flexibly worded, or the interview is a mix of more and less structured questions. Usually, specific information is desired from all the respondents, in which case there is a more structured section to the interview."*

The researcher ensured that questions were "short and to the point" (Boynton & Greenhalgh 2004:1314), the use of ambiguous, leading and invasive questions were avoided (Colosi 2006). Similarly, the use of abbreviations and jargons were completely avoided.

4.4. Data analysis

For the quantitative part, Statistical analysis (ANOVA) and regression analysis were conducted using SPSS Statistics 22 (IBM, New York, USA.) to test the correlation between building related health symptoms and building factors, including filtering, graphical analysis and summary statistics. Variables that previous studies have shown that are risk factor for the health symptoms such as age, gender and smoking were adjusted for. The correlation was then calculated and visualized to get the general view of the data and to identify correlations. P-values below 0.05 were considered significant for all analysis.

Likert-typed rating scale was used to obtain data on occupant's level of satisfaction with the indoor air quality and thermal comfort. Specifically, 7-point rating scales (1=extremely satisfied, 7=extremely dissatisfied) were used, adopted from Burge et al., (1987), Berry et al., (1996) and Raw (1995). Furthermore, Likert-type rating scales were also used to gather data on the prevalence of building related health symptoms in their previous and present dwellings. This method helped to gain numerical data that was easily analysed and interpreted using statistical analysis. The researcher envisaged that using standardized rating scales to determine perception of health, indoor air quality and thermal comfort would enable comparison of findings with previous studies. The prevalence of building related health symptoms in occupants' present dwellings (Passive houses) was then determined and compared with the prevalence in their previous dwellings.

The answers to the open-ended questions were thematically analysed Green et al., (2007), using Automated Coding Techniques with *"NVivo 12"* to aid the analysis process.

4.6. Building survey

During the International Passive House Open Days (from 8-10 June 2018), a survey of 6 Passive House dwellings was performed in Munich, Germany. This was conducted by the researcher through visual inspection using a form that documented information on features of Passive House buildings, such as the ventilation systems, floor coverings, operable windows, general observations of the tenants and experts about the ventilation and heating systems. When required, photographs were taken with the permission of the tenants (see Appendix C).

4.7. Interviews with Passive House Experts

Due to limited literature on Passive House Standard, interviews with the experts aim to investigate how the provision of thermal comfort and indoor air quality was addressed at the design phase and to examine if there is any kind of trade-offs between energy efficiency and indoor air quality, thermal comfort, and the use of the ventilation systems.

Semi-structured interviews were conducted with the Architects, Passive House Associations and Passive House Certifying bodies. Questions were structured into the following sections:

1. The ventilation systems and the risk of microbial (bacteria, mould) growth
2. Thermal comfort and indoor air quality design strategies of Passive House Standard
3. Adaptability of Passive House Standard to different climates.

Questions differed slightly between the building experts, depending on their level of involvement at different operational and design phases. For example, building maintenance and operation related questions were directed to the Passive House Associations, with questions relating to energy saving strategies addressed more towards the architects. Even though interview questions were prepared beforehand, the nature of the semi-structured interviews enable the conversation to unravel gradually (Longhurst 2010), allowing more engagement and flexibility.

According to Galletta (2013:24), who argues that semi-structured interviews are,

> *"sufficiently structured to address specific topics related to the phenomenon of study, while leaving space for participants to offer new meanings to the study focus."*

Transcripts were prepared after the interview to aid data analysis procedure. The study employed thematic analysis to examine and organize the data into themes. Green et al., (2007) outlined four steps of thematic data analysis: 1. Coding, 2. Data immersion, 3. Identifying themes, 4. Creating categories. Automated Coding Techniques with *"NVivo 12"* was used to aid the analysis process. According to Saldaña (2013: 37) "Coding is a cyclical process that requires you to recode not just once but twice (and sometimes even more)." Hence, themes were refined and developed repeatedly; informed by the theory at various stage of the process.

4.8. Research ethics

In compliance with the CEU Research Ethics Policy and Guidelines, only adults were allowed to participate in the survey and participation is voluntary. The very beginning of the questionnaire page contains a summary of information, assuring the respondents of anonymity and answers were kept completely confidential. It was emphasized that the researcher is an MSc student at CEU, with the email of the researcher.

Ethical considerations with respect to the interview process included providing respondents with the right to refrain from participating, desist from answering certain questions or withdraw as wishes (Brace 2008). The researcher prioritized data protection and informed respondents of how the data will be used. During the interview process, researcher avoided repetition of questions (Oppenheim 2005), long and tedious interview (Brace 2008). Moreover, care was taken when sensitive questions such as medical history, personal health, behaviours or activities were asked.

4.8. Research limitations

The study was limited by number of factors; primarily time, number of responses were lower than expected, the need for specialized knowledge in Passive House technologies and parameters for indoor environmental qualities, context and availability of information. However, actions were subsequently taken to lessen their effects on the overall study. These are discussed in more details in table 4.1.

Table 4.1 Research limitations

Limitations	Description	Strategies
Specialism	Multidisciplinary nature of research on Passive House Standard; specialization and knowledge in multitude of areas is required	Extensive literature review, meetings with experts from different discipline, findings presented at multidisciplinary conferences
Availability of Information	Access to information related to Passive House energy efficiency design strategies was limited	Information was sourced online. Contacts was made with various organisations within the design team to source data
Time	Time was limited due to the nature of the research	Limited data collection methods
Low response rate	Number of responses were lower than originally expected	Contrary to region specific conclusion, statistical generalization was sought
Confounding factors	Other risk factors that influence occupants' state of health aside indoor environmental quality and energy efficient design strategies of Passive Houses	Variables such as occupants' medical history, smoking status, number of occupants in the building, and their office environment Were adjusted for. However, other related factor such as stress could not be determined.
Self-reporting health status	It is difficult to verify whether responses reflect reality	Questions were readdressed if contradictory answers were given
Some tenants were reluctant to be recorded with Dictaphone during interviews		Information was documented as much as possible in the questionnaires

5.0. Results

This chapter presents the results of the perceived Passive House occupants' health, indoor environmental quality and thermal comfort from the six regions. In total, 98 people responded to the net based-questionnaire (Table 5.1), of which 7 were living in non-Passive Houses (Net-Zero Energy Home, Green Certified Home, Energy Plus Building). The study focuses on Passive House users, hence, respondents from non-Passive Houses were not included in the analysis. The results from the study is provided bellow.

Table 5.1 Summary of data collection results

Total number of responses from the net-based questionnaire:	98
Responses from the Passive House occupants:	**92**
Responses from Net-Zero Energy Home:	3
Responses from Green Certified Home	3
Responses from EnergyPlus Building	1
Questionnaire (face to face):	**6**
Interviewed stakeholders:	4

5.1. Characteristics of respondents (N=98)

First, personal characteristics of respondent was assessed based on the survey, including age, gender, smoking status and medical histories. In the total number of participants, 71% were male, 25.8% were female and 3.2% were transgender or unspecified (Table 5.2). Participants ranged in age from 18 to 65, with most age 55 or older (34%). Most of the participants have their buildings located in North American (21%), Central Europe (19%), Korean, Japan and China (19%), UK and Ireland (16%), Eastern Europe (14%) and Australasia/South Pacific (11%) respectively. Majority of the respondents were married or living with a partner and children (90.6%). 78.1% of respondents never smoked where the remaining 21.9% quite smoking more than 12 months before the survey. The average age of building was 4 years, ranging from below 2 to above 9 years (Table 5.3).

Table 5.2 Characteristics of respondents

Personal characteristics	%
Gender	
Male	71
Female	25.8
Unspecified	3.2
Age	
18-24 years	1
25-34 years	19
35-44 years	20
45-54 years	26
55 years or older	34
Building location	
North America	21
Central Europe	19
Korea, Japan, China	19
UK and Ireland	16
Eastern Europe	14
Australia/South Pacific	11
Smoking status	
Never smoked	78.1
Quit smoking	21.9
Smoke currently	0
Maintenance, e.g. cleaning	100

Table 5.3 Building age, year

Building age, years	**N**	**Percent, %**
below 4	1	0.98
4	77	75.5
5	2	1.96
6	5	4.9
7	3	2.94
8	1	0.98
9	4	3.9
Above 9	5	4.9

5.2. Indoor Air Quality Perception

5.2.1 Previous dwelling

Occupants were asked to rate their level of satisfaction with the indoor air quality in their previous dwellings before moving into Passive Houses. Only 8% of occupants were extremely satisfied, where another 20% were neither satisfied nor dissatisfied. 17% were moderately satisfied, 7% were slightly satisfied, where 3% were moderately dissatisfied, 22% were slightly dissatisfied and 23% were extremely dissatisfied (Figure 5.1).

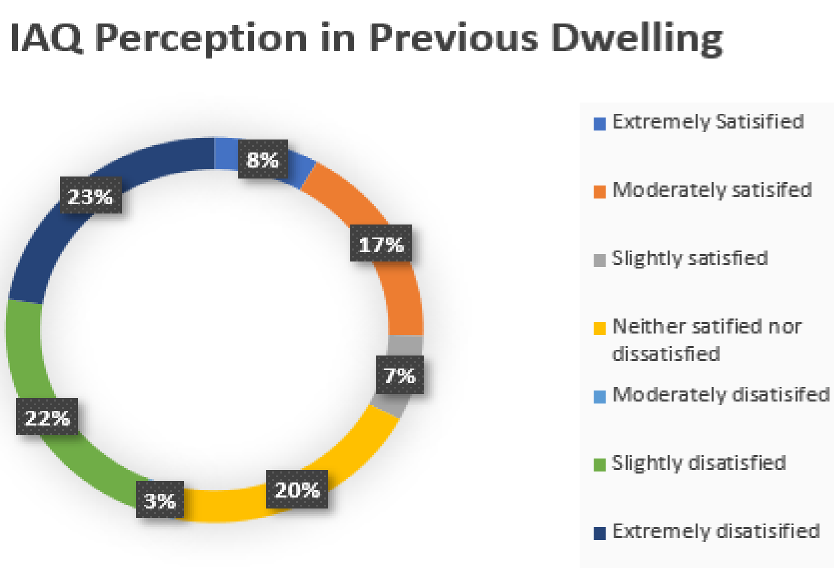

Figure 5.1 Indoor air quality perception in previous dwellings

5.2.2. Current dwellings (Passive Houses)

In general, majority of occupants (86%) were extremely satisfied with the indoor air quality in Passive Houses, where 11% were moderately satisfied, 1% were slightly satisfied, no report of neither satisfied nor dissatisfied, 1% were slightly dissatisfied and the remaining 1% were moderately dissatisfied (Figure 5.2), where Table 5.4 compared the results (in percentage) of perceived indoor air quality in both previous and current dwellings.

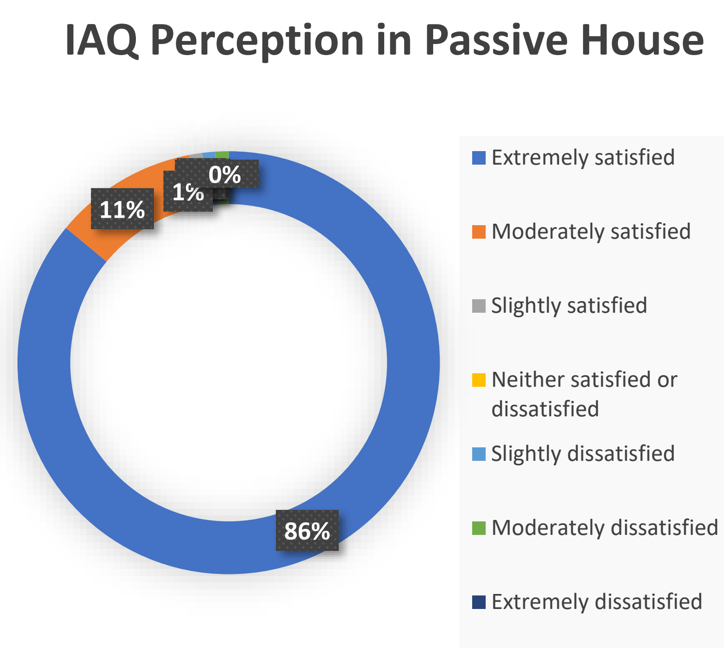

Figure 5.2 Indoor air quality perception in Passive Houses

Table 5.4 Perception of indoor air quality in both previous and current dwelling

Indoor air quality perception	previous dwellings, %	current dwellings, %
Extremely satisfied	8	86
Moderately satisfied	17	11
Slightly satisfied	7	1
Neither satisfied nor dissatisfied	20	-
Slightly dissatisfied	22	1
Extremely dissatisfied	23	-
No response	3	1

Based on standard rating scale, occupants were asked to rate indoor air quality of their previous and current dwellings. For Uni-polar scales such as fresh to stuffy, where 1 is considered fresh and 7 stuffy. In Passive Houses, the overall satisfaction scores of 1-1.5 was good and do not suggest any significant problems with the perception of the indoor air quality. As illustrated in Table 5.5, the overall satisfaction in their previous dwellings was 3-3.5. The results suggest issues with humidity with a score of 4 and fresh-stuffy score was 5 suggesting ventilation problem. The overall satisfaction score in this home was 3-3.5, suggesting poor indoor air quality. Finally, in previous dwellings, perception of fresh-stuffy was identified with a rating scale of 5 which is likely to be the cause of the low satisfaction score in previous dwellings.

Table 5.5 Average score for tenants' perception of indoor air quality

Indoor air quality factors	Previous dwellings	Passive House
Dry (1)-Humid (7)	4	3
Fresh (1)-Stuffy (7)	5	1
Odorless (1)- odorous (7)	2	1
Satisfactory overall (1)-unsatisfactory overall (7)	3	1

Note: Tenants were asked to rate indoor air quality factors on Uni-polar scale of 1-7 for example dry=1 to humid=7.

Table 5.6 shows results from the indoor air quality variables, mostly related to cigarette smoke, mould, food odour and dampness. At the baseline, in Passive Houses, 12% of respondents reported significantly less frequent odour related to construction materials, where 5.9% reported food odour on weekly basis, 0.98 reported odour related to traffic and 2.9% reported general stiffness, where no report of noticeable odours related to cigarette smoke, sewage smell and mould. One of the occupants writes "we *have been experiencing less dust, Less Carpet Mites, No Mould"*.

Table 5.6 Indoor air quality variables and occupants' perception

IAQ variables	N	Frequency
Odours		
Food		
No noticeable odour	73	-
Odour in the building	6	weekly
Odour elsewhere	12	often
Odour outside building	7	once a while
Cigarette smoke		
No noticeable odour	83	-
In the building	0	once a while
Elsewhere	14	once a while
Outside building	1	once a while
Mould odour		
No noticeable odour	96	-
In the building	0	-
Elsewhere	2	weekly
Outside building	0	-
Construction materials		
No noticeable odour	76	-
In the building	12	once a while
Elsewhere	8	often
Outside building	2	once a while
General stiffness		
No noticeable odour	79	-
In the building	3	daily
Elsewhere	0	-
Outside building	16	once a while

Smoke odour		
No noticeable odour	69	-
In the building	18	once a while
Elsewhere	9	weekly
Outside building	2	once a while
Traffic odour		
No noticeable odour	64	-
In the building	1	Once a while
Elsewhere	7	Weekly
Outside building	26	often

5.3. Thermal comfort perception

In Passive House dwellings, overall thermal comfort satisfaction during both winter and summer months was very good with average score of 1 in rating scale comfortable (1) to uncomfortable (7). Similarly, in summer months, average scores for the rating scale too warm (1) to too cold (4) were 2 and 2.5 respectively. In the winter months, average scores of 2 were reported for the too cold (1) to too warm (4), suggesting comfort satisfaction with the indoor temperature during both winter and summer months (Table 5.7).

Table 5.7 Average score for Passive House thermal comfort perception

Thermal comfort factors	Passive House
Summer	
Comfortable (1) - uncomfortable (7)	1
Too hot (1) - too cold (4)	2
Stable (1) - varies throughout the day (7)	1
Satisfactory overall (1) – unsatisfactory overall (7)	1
Winter	
Comfortable (1) - uncomfortable (7)	1
Too hot (1) - too cold (4)	2
Stable (1) - varies throughout the day (7)	1
Satisfactory overall (1) – unsatisfactory Overall (7)	1

Note: Tenants were asked to rate thermal comfort factors during both winter and summer months on a scale of 1-4 for example, too hot=1 to too cold=4
For example, the following illustrative quote from the stakeholder explained:

"During winter months, the small amount of heat that can be added to inlet fresh air through a ventilation system is adequate to keep Passive House at a comfortable temperature. During the summer months, strategic shading and aeration is sufficient to keep Passive House suitably cool, although in summer, humid climates, small scale air conditioning may be needed".

5.4. Ventilation system

Occupants were asked if they are satisfied with the MVHR system in their Passive Houses. Majority of occupants (88.2%) were extremely satisfied, where (5.6%) were neither satisfied nor dissatisfied, (1.96%) were satisfied except when cooking and the remaining (2.94%) were not satisfied (Table 5.8). Among the (2.94%) that were dissatisfied, one of them explained the "*ventilation system was noisy on higher settings*"; another occupant stated that "*the bathroom could use additional ventilation as they sometimes get steamy or smelly*". One occupant reported that *"the system is good, but installer's confidence exceeded their experience"*.

Table 5.8 Occupants' level of satisfaction with the ventilation system

Ventilation system	N	%
Extremely satisfied	87	88.2
Neither satisfied nor dissatisfied	6	5.8
Satisfied (except when cooking)	2	1.96
Dissatisfied	3	2.94

During the interview process, households and experts were asked if there are problems with bacteria, mould and drafts, indoor air, temperature and Passive House Standard adaptability to different climates. The comments of respondents are summarized below:

Mould growth, bacteria and noise:

"Unlike air conditioning system that recirculates indoor air, ventilation system in Passive House is a fresh air supply system, hence, mould can only grow in a poorly maintained recirculating air system. Sound control measures such as low air speed and mounting of vibration isolation help reduced noises from the ventilation system".

Indoor temperature and condensation:

"Thick insulation and airtightness in Passive House Standard prevent leaks through which moist air can enter the building envelope and stabilize indoor temperatures at around 20°C throughout the year, thus preventing microbial growth and condensation".

One of the architects were asked if MVHR system needs maintenance?

"Yes. Air filters should be replaced once or twice a year. The ductwork does not need to be cleaned because the filter normally protects it from dust. In case the ventilation system does not have automatic flow balancing, there is a need to recalibrate the airflow volume after many years".

MVHR/HRV and Natural ventilation system:

"The use of natural ventilation system (windows) can help reduce indoor air pollutants but it is not fit for energy efficient buildings. Houses with very high airtightness and very low energy use have a mechanical ventilation system and heat recovery. The system saves more than 10 times of heating energy compared to electric energy for running the ventilation system, and much more, it ensures a healthy indoor microclimate".

In Passive Houses and retrofits, the fresh air intake and the exhaust air outlet are usually positioned close to each other. Is there any risk that the fresh air will get mixed with the exhaust air?

"There are stern regulations in many countries for the separation of the fresh intake air from the exhaust air outlet. Experience from Passive House reveals that giving different directions of the airflow through the fresh intake air and the exhaust air outlet is sufficient to guarantee good air quality".

Adaptability of Passive House Standard to different climates

"Whether in the south or in the North, West or East, one of the features of Passive House is its consistency. The concepts are functional and founded on the capacity to heat the house wholly by the supply air. The concepts are not climate dependent. Rather, Passive Houses are designed to adapt to the climate in which it will be built, however, these requirements may be difficult to fulfil sometimes. For example, a Passive House in the North America would likely require more thermal protection than the one in South".

5.5. **Building related health symptoms (Sick Building Syndrome)**

5.5.1. Sick Building Syndrome Symptoms in Previous Dwelling

Respondents were asked if they or member of their household have been affected by sick building syndrome symptoms in their previous dwelling; Sick building syndrome symptoms such as asthma, headache, sleeping problems or other respiratory symptoms from allergies. In total, 42% of all respondents reported they have not been affected by sick building syndromes, where 56 % reported they have been affected, and the remaining 2% did not answered the question. Thus, the prevalence of sick building syndrome symptoms was then investigated among the 56% that have been affected in their previous dwellings.

Respiratory Complaints and Sleeping Problems

As rightly indicated, among 56% who reported cases of sick building syndrome symptoms, 4% reported they were affected by Upper respiratory tract symptoms daily, where 13% reported that they experienced it on weekly basis and 39% on monthly/less frequently. However, only 4% reported that the symptom was better away from home. The most prevalent building related health symptoms (56%) among occupants was Upper respiratory tract symptoms (dry or sore throat, common cold, runny nose), with none reporting the symptoms to be better away from home.

On a similar trend, 31% experienced Lower respiratory tract symptoms, with 14% experiencing it on weekly basis, 10% on monthly/less frequently, where 7% were affected daily, with 8% stating that the symptoms were better sometimes when away from home. Sleeping symptom was experienced by 29% of occupants, general symptoms were experienced by 22%, where 9% experienced muscle pain and 5% experienced joint pain respectively. As noted by Murphy (2006), when more than 20% of tenants report symptoms derived from the ASHARE definition of acceptable indoor air quality, a "sick building" is declared.

Allergies

In total, 31.8% of all respondents reported cases of allergies. The most common types of allergies affected by participants were pollen allergy (28%), where 8.1% reported they were affected daily, where 11.2% experienced it on weekly basis and the remaining 11.7% reported they were affected monthly/less frequently. 21.3% reported cases of dust mite allergy, where 8.2% were affected by food allergy respectively. Figure 5.3 presents the results.

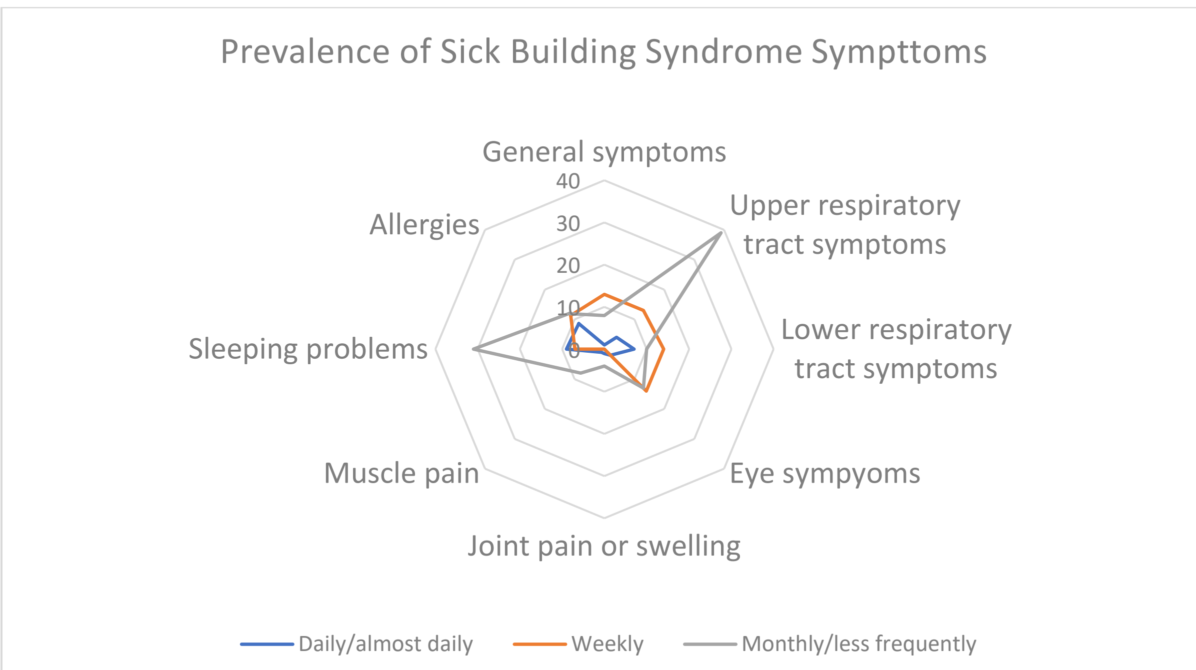

Figure 5.3 Frequency of Sick Building Syndrome symptoms (percentage) experienced by occupants in previous dwellings

Finally, respondents were asked to briefly describe and rate their health condition and that of their household in their previous dwellings on a scale of 5, ranging from very good (1) to very bad (5). 25% reported a very good health condition (1), a larger percentage (69.8%) reported that their health was good (2), where 10% reported a moderate health condition (3) and the remaining 1.2% percent reported poor health (4). Figure 5.4 presents the results.

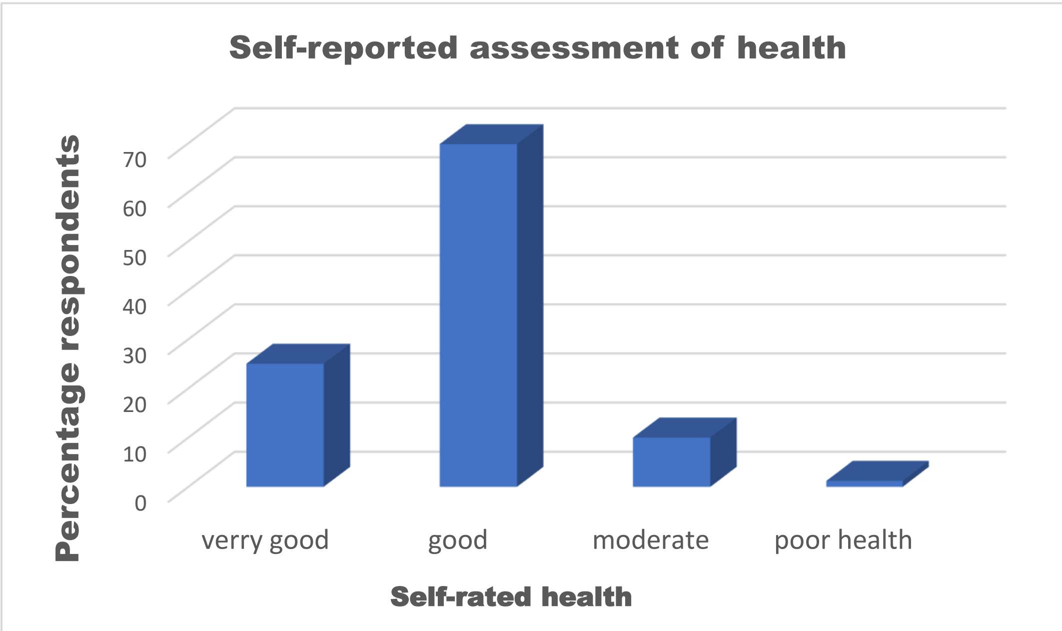

Figure 5.4. Frequency of self-reported assessment of occupants' health condition in previous dwelling

Some of the respondents explained:

"*As a family of five, we were much more susceptible to summer allergens as well as having mold in our previous home"*

"Seemingly normal. However, in hindsight I believe there was more seasonal allergy and seasonal flu symptoms"

"Frequent colds throughout the year, spring-time allergies, and our son had frequent nose-bleeds due to dry air"

"Our health condition was normal. The apartment had only window air conditioning units which were noisy, and we did not like to run them much. It was therefore much more humid during the summers than in our current house"

"My wife and son had respiratory problem"

"Nothing extraordinarily bad. The usual problems of seasonal/environmental allergies"

5.6. Sick Building Syndrome Symptoms in Passive House

Symptoms reported were less common in Passive Houses than in previous dwellings. Occupants were asked if they have experienced Sick Building Syndrome Symptoms since they have been living in Passive Houses, 78.2% reported that they have no such experience, where 21.8% reported they have experienced it. Compared to dwellings with natural ventilation, living in a house with a mechanical ventilation system was related to a reduced prevalence of building related health symptoms and general symptoms. Unlike buildings with other type of ventilation systems, dwellings with mechanical ventilation and exhaust ventilation system have a higher mean air rate. As stated above, building related health symptoms were reported in Passive Houses; however, this is not of significant concern considering their low prevalence rate.

To determine the most prevalent health symptoms in Passive Houses, those who reported cases of Sick Building Syndrome Symptoms were asked to select symptoms they experienced and the frequency, giving options ranging from daily to monthly or less frequently. In general, the prevalence of diseases of health indicator were higher in previous dwellings, however, the prevalence of dry eyes (8.2%) was significantly higher in Passive Houses compared to previous dwellings ($p < 0.05$).

5.2% reported daily cases of general symptoms, 3% reported occurrence of upper respiratory tract symptoms monthly/less frequently, where 1% reported experience of lower respiratory tract symptoms monthly, 1% reported cases of muscle and joint pain, where the remaining 3.4% reported cases of allergies occasionally (Figure 5.5). However, 1.8% claimed that the symptoms were not related to building. Table 5.9 compares the frequency of Sick Building Syndrome Symptoms in both previous and present dwellings, where coefficients and significance are indicated in Table 5.10.

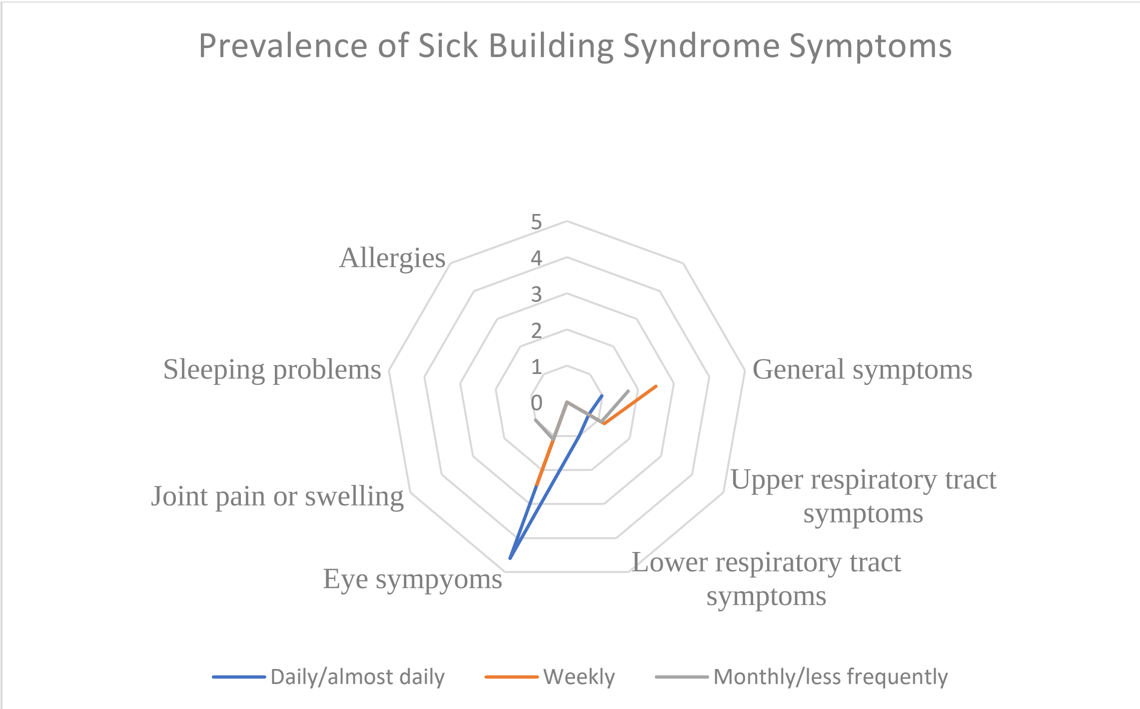

Figure 5.5 Prevalence of Sick Building Syndrome symptoms (percentage) experienced by occupants in Passive Houses

Some of the respondents explained:

"*We have seasonal colds, but they don't linger. My husband has always been a light sleeper, but we sleep much better because of the sound insulation. We live right by a major airport and planes fly over constantly"*

"Comfort-level definitely improved; but health wise, there has not been major changes. We are in a different area and it is environmentally distinct. It is very hard to attribute any ailment specifically related to the house. The one noticeable change beyond air quality is the hardness of the water".

"Seasonal allergies still affect my family but to a lesser extent than in the previous home".

"Better health and much more comfortable"

"Improved. Decreased frequency of illness for all members of the family, especially noticeable in winter season".

"Quality of living is very much improved"

"Healthier. Less seasonal colds. Less allergy symptoms. Further, in last year's summer forest fire season, the smoke from the air was significantly removed by the HRV filters".

"I've noticed I rarely get a cold, where it seemed frequent before. Our son gets fewer nose-bleeds in the new home. Being inside our home helps mitigate the seasonal allergies in the spring".

"If we open windows, pollen will come indoors and trigger allergies, but if we keep windows closed, then almost all of the pollen is filtered out of the air and we have almost no allergies. Again, this is only seasonal (April through June when many plants are blooming)".

"Our health is normal. We occasionally suffer cold/flu in winter time but none of that changed compared to the previous dwelling. We experience higher level of satisfaction from living in a conditioned space at a very low impact to environment".

"Better indoor climate. Less humidity".

Finally, occupants were asked to comment on the environmental condition of their passive houses:

"Our whole house filter system is changed every 6 months and collects a lot of particulates".

"We suffered from VOC when we first moved in. We couldn't find zero- or low- VOC stains. We let the house air out for a month before moving in. Today we still notice a faint VOC smell when we enter the house after being away for a few days or longer. Then we no longer notice it. When we go to other people's homes, we notice the various smells more acutely".

"Excellent Indoor air quality"

"No Remaining interior mold issues (which had been present in the previous dwelling due to poor ventilation and moisture condensation, especially in wintertime)"

"feel just comfortable, much easier than before"

"Much less dry in winter, which is nice. We do have to run A/C from April to October and wish that we were slightly warmer in winter".

"We began with mold problems due to exterior drainage issues. Once they were sorted, we became happier with the air quality. Some of our air issues have to do with this as a retrofit rather than new construction".

"Very comfortable; reduced allergies"

"Consistent interior surface temperatures. Exterior noises significantly dampened. Moisture and odors from kitchen and bathroom use is quickly and effectively removed. The interior space is as clean and peaceful as you want it to be".

"In our previous home we sometimes needed to add moisture to the air on the coldest and driest days of winter, but we never need to add moisture to the air in our Passive House. The relative humidity stays comfortable (above 30%)".

"In the other section, I selected food smells - these are from our cooking - both inside and outside, since we use the range hood vent. I also selected traffic smell inside and outside. This is not exactly from traffic but rather the steel industry present within 15 miles. The air quality of our city is known to have problems, and bad smelling air days occur with regularity. On those days, when the air smells bad with industrial smell outside, it also does smell so indoors. We attribute this effect in part to the continuous ventilation - which has MERV 13 filters but does not have any carbon (or VOC removing) filter. I think we will be retrofitting our ventilation system with such a carbon filter".

Table 5.9 Prevalence of SBS in both previous and current dwellings

SBS symptoms (frequency)	previous dwellings %	current dwellings %
SBS symptoms		
Yes	56	21.8
No	42	78.2
Upper respiratory symptoms		
Daily	4	-
Weekly	13	1
Monthly/less frequently	39	2
Lower respiratory symptoms		
Daily	7	-
Weekly	14	1
Monthly/less frequently	10	-
General Symptoms		
Daily	3.8	1.2
Weekly	9.2	3.1
Monthly/less frequently	9	0.9
Allergy (pollen)		
Daily	8.1	-
Weekly	11.2	1.2
Monthly/less frequently	11.7	-
Allergy (dust mite)		
Daily	9.2	-
Weekly	4.3	-
Monthly/less frequently	7.8	
Allergy (food)	8.2	-
Sleeping problems		
Daily	2.9	2.2
Weekly	8.2	-
Monthly/less frequently	18.7	-
Joint and muscle pain		
Daily	1.4	1
Weekly	3.1	-
Monthly/less frequently	9.5	-
Dry eyes		

Daily	-	5.2
Weekly	-	1.8
Monthly/less frequently	0.8	1

Table 5.10 Coefficients and significance

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
1 (Constant)	6.290	.700		8.985	.000	4.900	7.680
Your household have had in your previous house and how often? (General symptoms and allergies)	-.187	.149	-.128	-1.256	.212	-.482	.108
Your household have had in your previous house and how often? (Upper respiratory tract symptoms)	-.201	.149	-.137	-1.351	.180	-.497	.094
Your household have had in your previous house and how often? (Lower respiratory tract symptoms)	-.034	.149	-.024	-.230	.818	-.331	.262
Your household have had in your previous house and how often? (Eye symptoms)	.181	.143	.128	1.266	.209	-.103	.464

Since **p>0.05** (from the **Sig.** column in the **Table 5.8** above, the values of **p** are **0.212, 0.180, 0.818** and **0.209** respectively for the two independent variables), we have the statistical reason (using multiple regression analysis in SPSS) to conclude that the prevalence of health symptoms is more frequent in Non-Passive house than in Passive Houses.

In a similar trend, occupants were asked to briefly describe and rate their health condition in Passive Houses on a scale of 5, with very good (1), good (2), moderate (3), bad (4) and very bad (5). Most individuals (82%) rated themselves as having very good health (1) than when living in their previous dwellings, where 11% rated their health has good (2), 6% reported moderate health (3) and 1% reported poor health. Figure 5.6 present the results, where Table 5.9 compares the results in both previous and current dwellings.

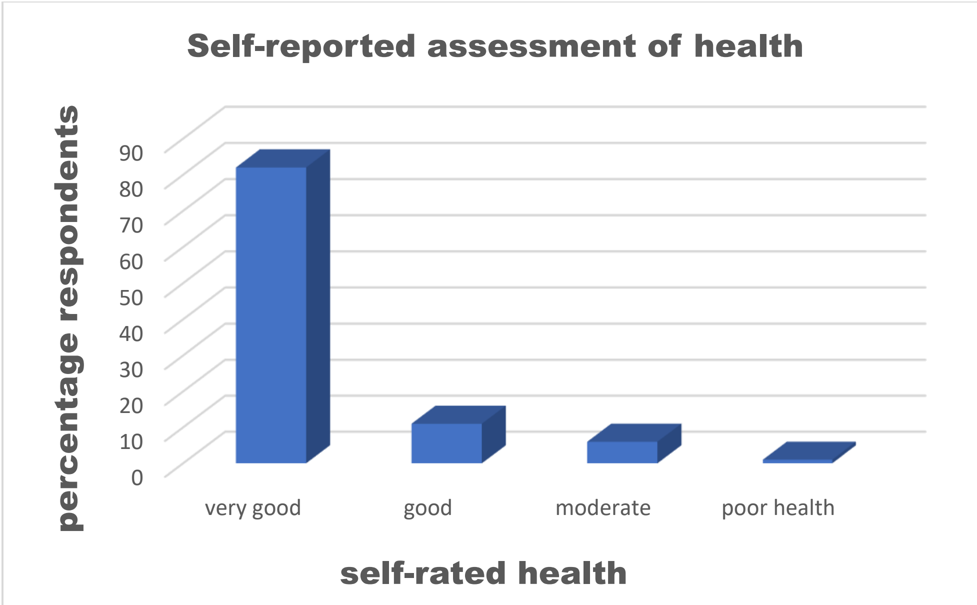

Figure 5.6. Frequency of self-reported assessment of occupants' health condition in previous dwelling

Table 5.11. Self-health report in both previous and current dwellings

Self-rated health	previous dwellings, %	current dwellings, %
Very good	25	82
Good	69.8	11
Moderate	10	6
Poor health	1.2	1

Compared with previous housing situation, participants were more satisfied with their current dwellings conditions. Table 5.12 shows the coefficient and significance.

Table 5.12 Coefficients and significance

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
1(Constant)	2.812	.788		3.569	.001	1.248	4.377
How satisfied were you with the indoor air quality in your previous house	.129	.086	.153	1.504	.136	-.041	.298
Briefly describe health condition in your previous house	.002	.163	.001	.010	.992	-.322	.325

Since **p>0.05** (from the **Sig.** column in the **Table 5.7** above (the values of **p** are **0.136** and **0.992** respectively for the two independent variables), we have the statistical reason (using multiple regression analysis in SPSS) to conclude that Passive House Standard provides good indoor climates which eventually improves the health of occupants.

6.0. Discussion

To the knowledge of the researcher, besides the studies conducted by Peter et al (2017), Takaro et al (2011) and Leech et al (2004) on highly energy efficient buildings, this research was one of the first studies investigating the perceived health of occupants in Passive Houses. The inspiration to conduct this study was as a result of several Passive House conferences the researcher have attended, orchestrated by the researcher's supervisor (Prof. Mrs. Diana).

6.1 Prevalence of building related health symptoms (Sick Building Syndrome)

The prevalence of Sick Building Symptoms in previous and present dwellings (Passive Houses) was evaluated using validated questionnaire. In the previous dwellings, the study found a generally high prevalence of sick building syndrome symptoms as compared to their current dwellings. Symptoms of highest prevalence in previous dwellings include Upper respiratory tract symptoms such as stuffy nose, common cold and dry throat (56%), of which 4% reported they were affected daily, 13% reported they were affected weekly and 39% monthly or less frequently. Prevalence of sleeping problem is again alarming as 47% reported they were affected by slapping problem. However, 31% reported they experienced less frequently. In a similar trend, 31.8% reported cases of allergies of different types ranging from food to pollens and dust mite, where 8.6% were affected daily, 11.3% were affected weekly and 11.9% were affected less frequently. These symptoms are similar to those experienced after exposure to high level of indoor pollutants such as Volatile Organic Compound, Carbon Monoxide, Mould and pollen, household products and pesticides including different construction materials, e.g., lead and formaldehyde (as described in chapter 3), but may be due to different other factors and therefore not conclusive.

Significant differences were observed regarding the prevalence and number of virtually all building related health complaints and other minor ailments. Allergies against insects, pollens and dust mites were less frequent in Passive Houses. However, some respondents (8.2%) suffered significantly more frequently from dry eyes compared with when in previous homes. The reason might be due to lower humidity in energy efficient homes with mechanical ventilation systems (US-Department of Energy 2017).

Building related health symptoms also known as Sick Building Syndromes are if building occupants suffer from a certain symptom within the last 1 year, and if the symptom gets better whenever occupants are away from home. To the knowledge of the researcher, this concept of sick building is simplistic and relatively myopic considering different risk factors involved; such as psychological, chemical, biological, physical aspects. Moreover, the concept was designed to investigate office buildings and complexes with a huge number of users and may not be completely applicable to residential houses.

According to Pendleton (2002:17):

> *"a building can be referred to as sick whereby 20% of the building inhabitants experience acute health and comfort effects that lead to decrease in intensity or disappear when away from the building and continues for more than two weeks"*

Nevertheless, in the absence of method that is design strictly for residential buildings, the concept provides a universal approach to investigate the frequency of building related health symptoms, and for comparison between buildings. This limitation therefore provides an opportunity for the development of a specialised method to investigate sick buildings in a limited survey responses and household sizes.

6.2 Self-rated health

Respondents rated their state of health and that of their household in Passive Houses higher than when living in their previous dwellings. The results from this study is in line with a study conducted by Peter et al (2017) on “Health and Wellbeing of Occupants in Highly Energy Efficient Buildings”. Furthermore, having lived in Passive House for 4 years (mean score of building age), occupants perceived significantly more frequent improvements in their state of health. In part, this might be explained by the better indoor air quality and thermal comfort in Passive House Standard (Peter et al 2015, Schneider 2006). In the investigation conducted by Leech et al (2004) on “Health in occupants of energy efficient new homes”, Leech discovered that new users of energy efficient buildings with mechanical ventilation and heat recovery systems generally reported an improvement in health as compared to occupants in control homes with natural ventilation.

6.3 Indoor Air Quality Perception

Respondents were asked to rate the level of satisfaction with the quality of indoor air in their previous and current dwellings (Passive Houses) using overall satisfaction scores (rating scale: satisfactory overall (1) - unsatisfactory overall (7)). Occupants did not report dissatisfaction of any sort with the quality of the indoor air in their current dwellings. Satisfaction with housing and indoor air was very high in Passive Houses in both winter and summer months with 86% of occupants reported they were extremely satisfied with the overall rating scale of 1-1.5, compared with 7.8% that reported they were extremely satisfied with the indoor air quality in their previous dwellings (score greater than 3), this indicates that majority of the households were not satisfied with the indoor air.

According to the results of perception of indoor air quality, there were highly significant differences regarding the subjectively perceived indoor air quality between previous and current dwellings, with a perceived higher quality of air in the current dwelling. Similarly, air movement and temperature were rated significantly more pleasant in the current dwellings.

6.4 Thermal Comfort Perception

Building occupants were also asked to rate thermal comfort in their current dwellings. The results suggest high level of satisfaction with the comfort perception both in winter and summer months. For instance, overall thermal comfort satisfaction during both winter and summer months was very good with an average score of 1 in rating scale comfortable (1) to uncomfortable (7). For the rating scale 'too hot (1) to too cold (4), the mean score was 2-2.5 respectively, indicating that they perceived the indoor environment suitably warm in winter and in summer season.

6.5 Key study limitations and future recommendation

This study analysed direct relationship between Passive House technologies and occupants' health and well-being. However, indoor environmental quality such as air and thermal conditions also have high level of impact on occupants' health. Whilst this study explores under-researched area, lots need to be done to improve level of awareness and knowledge of the hidden health benefits of Passive House Standard. Although, majority of occupants reported high level of satisfaction with the indoor air quality in Passive Houses, however, some occupants (less than 1%) reported that they were exposed to VOC in their first few weeks upon arrival. To reduce exposure to indoor air pollutants such as VOC, occupants should have been advised when moving into the home to maintain high level of ventilation rates for a period of 3 to 4 weeks.

It is hoped that these findings may help to foster further studies in this area, most especially impacts of energy efficient design strategies on indoor air quality. The study limited its focus on residential houses built to Passive House Standard, it creates different research trends on indoor environmental quality in modern-day highly energy efficient buildings such as Passive Houses. From this state of art study, researchers can develop a study that investigate health effects of indoor environment in schools.

6.6. Conclusion

As discussed in chapter 2, the need for energy efficiency in building sector will continue to rise. All newly built buildings should be "near zero energy buildings" by year 2020, and the major leap in the direction of near zero energy buildings is Passive House Standard. A significant amount of greenhouse gas emission can be reduced, and large amount of energy can be saved by renovating existing buildings into Passive House Standard. Passive House retrofit has proven to work in practice as discussed in section 2.5.

Occupants of Passive Houses generally rated their health, thermal comfort and the quality of the indoor air better compared with when living in their previous dwellings. However, a certain percentage (8.6%) of respondents reported cases of dry eyes more frequently in Passive Houses than when in previous dwellings. This study shows that there are no health reasons not to apply Passive House Standard.

REFERENCES

Andersen, R.V., Toftum, J., Andersen, K.K. & Olesen, B.W. 2009, Survey of occupant behaviour and control of indoor environment in Danish dwellings, *Energy and Buildings*, vol. 41, no. 1, pp. 11-16.

Anderson, R. V.,_Bakke, J., Bjørseth, O., Bornehag, C., Clausen, G., Hongslo, J., Kjellman, M., Kjaergaard, S., Levy, F. & Mølhave, L. 1998, TVOC and Health in Non-industrial Indoor Environments, *Indoor air*, vol. 7, no. 2, pp. 78-91.

ASHRAE 2014, *ASHRAE rules of the board. https://www.ashrae.org/society-groups/rules-ofthe-board.*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

_________ 2013a, *ASHRAE Handbook- Fundamentals (SI Units)*, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Atlanta.

2013b, *Standard 62.1-2013, Ventilation for acceptable indoor air quality*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

__________2009, *Indoor air quality guide, best practices for design construction and commissioning*, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta.

Bas, E. 2004, *Indoor air quality: A guide for facility managers*, 2nd edn, The Fairmont Press, Inc., Lilburn, Georgia.

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*, vol. 55, no. 1, pp. 4-14.

Balvers, J., Boerstra, A.C. & Van Dijken, F. 2011, An investigation into re-entrainment of exhaust air in mechanically ventilated dwellings, *Proceedings of the 12th International Conference on Indoor Air Quality and Climate*ISIAQ, Austin, Texas, 5-10th June, pp. 2394.

Berry, R.W., Brown, V.M., Coward, S.K.D., Crump, D.R., Gavin, M., Grimes, C.P., Higham, D.F., Hull, A.V., Hunter, C.A., Jeffery, I.G., Lea, R.G., Llewellyn, J.W. & Raw, G.J. 1996a, *Indoor air quality in homes Part 2: Annexes, The Building Research Establishment Indoor Environment Study*, BRE Press, Watford.

Berry, R.W., Brown, V.M., Coward, S.K.D., Crump, D.R., Gavin, M., Grimes, C.P., Higham, D.F., Hull, A.V., Hunter, C.A., Jeffery, I.G., Lea, R.G., Llewellyn, J.W. & Raw, G.J. 1996b, *Indoor air quality in Homes: Part 1, The Building Research Establishment Indoor Environment Study,* IHS BRE Press, 1-118, Bracknell.

Boer, R.d. & Kuller, K. 1997, Mattresses as a winter refuge for house-dust mite populations, *Allergy*, vol. 52, no. 3, pp. 299-305.

Bone, A., Murray, V., Myers, I., Dengel, A. & Crump, D. 2010, Will drivers for home energy efficiency harm occupant health, *Public Health Perspectives*, vol. 130, no. 5, pp. 233-238.

Bowling, A. 2005, Mode of questionnaire administration can have serious effects on data quality, *Journal of public health*, vol. 27, no. 3, pp. 281-291.

Building Research Establishment 2012a, *BREEAM Multi-residential 2008*, BRE Global, Watford.

_______2012b, *BREEAM Refurbishment Domestic Buildings- Technical Manual*, BRE Press, Watford.

________2006a, *EcoHomes 2006- The environmental rating for homes*, BRE Press, Watford.

________2006b, *Energy efficient ventilation in dwellings: A guide for specifiers, GPG268,* Energy Saving Trust, London.

Burge, S., Hedge, A., Wilson, S., Bass, J.H. & Robertson, A. 1987, Sick building syndrome: a study of 4373 office workers, *The Annals of Occupational Hygiene*, vol. 31, no. 4A, pp. 493-504.

Castagna M., Schmitt Y., Troi A. 2008. Analysis and optimization of a monitored passive house in Italy with dynamic simulation. *12. Intern. Passivhaustagung*, Nürnberg

Clausen, G., Bekö, G., Corsi, R.L., Gunnarsen, L., Nazaroff, W.W., Olesen, B.W., Sigsgaard, T., Sundell, J., Toftum, J. & Weschler, C.J. 2011, Reflections on the state of research: indoor environmental quality, *Indoor air*, vol. 21, no. 3, pp. 219-230.

Colome, S., McCunney, R., Samet, J. & Swankin, D. 1994, *Indoor air pollution: an introduction for health professionals, American Lung Association, American Medical Association, US Consumer Product Safety Commission, Environmental Protection Agency,* US Government Printing Office, Washington.

Crump, D., Dengel, A. & Swainson, M. 2009, *Indoor air quality in highly energy efficient homes- A review, NF 18,* IHS BRE press, Watford.

Dales, R., Liu, L., Wheeler, A.J. & Gilbert, N.L. 2008, Quality of indoor residential air and health, *Canadian Medical Association Journal*, vol. 179, no. 2, pp. 147-152.

Dimitroulopoulou, C., Crump, D., Coward, S.K.D., Brown, V., Squire, R., Mann, H., White, M., Pierce, B. & Ross, D. 2005, *Ventilation, air tightness and indoor air quality in new homes*,mBRE Press, Watford.

________2012, Ventilation in European dwellings: A review, *Building and Environment*, vol. 47, pp. 109-125.

Duijve, M. J. (2012). *Comparative assessment of insulating materials on technical, environmental and health aspects for application in building renovation to the Passive house level* (master's thesis).

Eick, S.A. & Richardson, G. 2011, Investigation of different approaches to reduce allergens in asthmatic children's homes — The Breath of Fresh Air Project, Cornwall, United Kingdom, *Science of The Total Environment,* vol. 409, no. 19, pp. 3628-3633.

Engvall, K., Wickman, P. & Norbäck, D. 2005, 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,* vol. 15, no. 2, pp. 120-126.

Environmental Protection Agency 2003, *Particle Pollution and Your Health*, United States Environmental Protection Agency, Indoor Environments Division, Office of Radiation and Indoor Air, Washington.

________2013, *Questions About Your Community- Indoor Air* [Homepage of Environmental Protection Agency], [Online]. Accessed May 21, 2018 Available: http://www.epa.gov/region1/communities/indoorair.html

________2004, *Biological Pollutants' Impact on Indoor Air Quality, Environmental Protection Agency.* Accessed May 20, 2018 *Available:* http://www.epa.gov/indoor-air-quality-iaq/biological-pollutants-impact-indoorair-quality

EPA & NIOSH 1991, *Building Air Quality - A Guide for Building Owners and Facility Managers, Environmental Protection Agency and National Institute for OccupationalnSafety and Health,* DHHS (NIOSH), 91-114, Washington, DC.

Fang, L., Clausen, G. & Fanger, P.O. 1998, Impact of temperature and humidity on the perception of indoor air quality, *Indoor air,* vol. 8, no. 2, pp. 80-90.

Fanger, P. & Christensen, N. 1986, Perception of draught in ventilated spaces, *Ergonomics,* vol. 29, no. 2, pp. 215-235.

Feist, W., Pfluger, R., Schnieders, J., Kah, O., Kaufmann, B., Krick, B., Bastian, Z. & Ebel, W. 2012, *Passive House Planning Package Version 7: Requirements for a quality approved Passive House*, Passivhaus Institute, Darmstadt, Germany.

Feist, W., Schienders, J., 2009. Energy efficiency – A key to sustainable housing. *The European Physical Journal Special Topic*, 176, pp. 141-153.

Gagnon, Y. 2010, *The case study as research method, A practical handbook,* Presses de l'Université du Québec, Québec.

Galletta, A. 2013, *Mastering the semi-structured interview and beyond: From research design to analysis and publication,* NYU Press, New York.

Gupta, R. & Dantsiou, D. 2013, Understanding the Gap between as Designed and as Built Performance of a New Low Carbon Housing Development in UK in *Sustainability in Energy and Buildings*, eds. A. Hakansson, M. Höjer, R.J. Howlett & L.C. Jain, Springer, pp. 567-580.

German Working Group on Indoor Guideline Values of the Federal Environmental Agency and the State's Health Authority 2008, *Health evaluation of carbon dioxide in indoor air Gesundheitliche Bewertung von Kohlendioxid in der Innenraumluft*.

Gurjar, B.R., Molina, L.T. & Ojha, C.S.P. 2010, *Air pollution: health and environmental impacts,* CRC Press, London.

Green J, Willis K, Hughes E, Small R, Welch N, Gibbs L, Daly J, Green J, Willis K, Hughes E, Small R, Welch N, Gibbs L, Daly J, Green, J., Willis, K., Hughes, E., Small, R., Welch, N., Gibbs, L., Daly, J., Green, J., Willis, K., Hughes, E., Small, R., Welch, N., Gibbs, L., Daly, J., Green, J., Willis, K., Hughes, E., Small, R., Welch, N., Gibbs, L. & Daly, J. 2007, "Generating best evidence from qualitative research: the role of data analysis", *Australian and New Zealand Journal of Public Health,* vol. 31, no. 6, pp. 545-550.

Greene, J.C., Caracelli, V.J. & Graham, W.F. 1989, Toward a conceptual framework for mixed-method evaluation designs, *Educational evaluation and policy analysis,* vol. 11, no. 3, pp. 255-274.

Hasselaar, B.L.H., 2004. *Vernieuwbare isolatie als duurzaam alternatief: een onderzoek naar de prestaties van vernieuwbare isolatiematerialen*. MSc thesis. Delft University of Technology. (in Dutch).

Hasselaar, E. (2008). Health risk associated with passive houses: an exploration. *Proceedings of Indoor Air*, 17-22.

Hemsath, T.L.; Walburn, A.; Jameton, A.; Gulsvig, M. 2012. A review of possible health concerns associated with zero net energy homes. J. Hous. Built Environ. pp. 389–400.

Hill, D. 1999, *Field Study of Heat Recovery Ventilation Systems,* Canadian Mortgage and Housing Corporation., Ottawa, Ontario.

Hong, S.H., Gilbertson, J., Oreszczyn, T., Green, G. & Ridley, I. 2009, A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment, Building *and Environment,* vol. 44, no. 6, pp. 1228-1236.

IPHA (International Passive House Association). Passive House Guidelines. Available online: https://www.passivehouse-international.org. Accessed: 12 May 2018

PHI (Passive House Institute). Energy efficiency of the Passive House Standard: Expectations confirmed by measurements in practice, 2011. Available online:

https://passipedia.org/operation/operation_and_experience/measurement_results/energy_use_measurement_results. Accessed: 8 June, 2018

Kulovesi, K., Morgera, E., & Muñoz, M. (2011). Environmental integration and multi-faceted international dimensions of EU law: Unpacking the EU's 2007 climate and energy package. *Common Market L. Rev.*, *48*, 829.

Krainer, A. 2008, Passivhaus contra bioclimatic design, *Bauphysik,* vol. 30, no. 6, pp. 393- 404.

Langer, S. & Bekö, G. 2013, Indoor air quality in the Swedish housing stock and its dependence on building characteristics, *Building and Environment,* vol. 69, pp. 44-54.

Larsen, T.S. 2011, Overheating and insufficient heating problems in low energy houses up to now call for improvements in future, *REHVA Journal,* vol. 48, no. 3, pp. 36-40.

Leaman, A. & Bordass, B. 2001, Assessing building performance in use 4: the Probe occupant surveys and their implications, *Building Research & Information,* vol. 29, no. 2, pp. 129-143.

Leech, J., Raizenne, M. & Gusdorf, J. 2004, Health in occupants of energy efficient new homes, *Indoor air,* vol. 14, no. 3, pp. 169-173.

Longhurst, R. 2010, *Semi-structured interviews and focus groups. In Clifford, French, & Valentine, Key methods in geography.* Sage, London.

Lowe, R. & Johnston, D. 1997, *Mechanical Ventilation with Heat Recovery in Local Authority, Low-Rise Housing: Final Report on the Derwentside Field Trial*, Leeds Metropolitan University, Leeds.

Less., B. & Walker., I. 2013, Indoor air quality and ventilation in residential deep energy retrofits, *ASHRAE IAQ 2013 Proceedings: Environmental Health in Low Energy Buildings.*ASHRAE, Vancouver, October 15-18th, pp. 553.

Letz, G.A. 1990, Sick Building Syndrome: Acute Illness among Office Workers: The Role of Building Ventilation, Airborne Contaminants and Work Stress, *Allergy Proceedings.,* vol. 11, no. 3, pp. 109-116.

Levin, H. 2005, Integrating indoor air and design for sustainability, *Proceedings of Indoor Air 2005,* ISIAQ, Beijing, China, September 4-9th.

Li, Y., Leung, G., Tang, J., Yang, X., Chao, C., Lin, J., Lu, J., Nielsen, P.V., Niu, J. & Qian, H. 2007, Role of ventilation in airborne transmission of infectious agents in the built environment–a multidisciplinary systematic review, *Indoor air,* vol. 17, no. 1, pp. 2-18.

McGill, G., Oyedele, L. & McAllister, K. 2015a, An investigation of indoor air quality, thermal comfort and sick building syndrome symptoms in UK energy efficient homes, *Smart and Sustainable Built Environment*, vol. 4, no. 3, pp. 329-348.

McGill, G., Oyedele, L. & McAllister, K. 2015b, Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing, *International Journal of Sustainable Built Environment*, vol. 4, no. 1, pp. 58-77.

McGregor, A., Roberts, C. & Cousins, F. 2012, *Two Degrees- The built environment and our changing climate,* Routledge, Oxon.

Milne, M., Gomez, C., & Epailly, G. (1996, October). Picturing the hidden environmental benefits of passive building design decisions. In *Proceedings of The National Passive Solar Conference* (Vol. 21, Pp. 288-293). American Solar Energy Society Inc.

Mlecnik, E., Kaan, H., & Hodgson, G. (2008). Certification of passive houses: a Western European overview. *PLEA Dublin 2008, 1061-1066. (2008)*.

Molina, C., Pickering, C., Valbjoern., O. & Bortoli, M.D. 1989, *Sick building syndrome: A practical guide, Environment and Quality of Life, European Concerted Action: Indoor Air Quality & it's Impact on Man, COST Project 613, Report No.4*, Commission of the European Communities, Luxembourg.

Mori, K. & Scearce, C. 2011, *Hygiene in the industrial world, an unhealthy obsession with cleanliness* [Homepage of Proquest], [Online]. Available: http://www.csa.com/ discoveryguides/hygiene/review.pdf

Ole Fanger, P. 2006, What is IAQ? *Indoor air*, vol. 16, no. 5, pp. 328-334.

Papadopoulos, A.M., 2005, State of the art in thermal insulation materials and aims for future developments. *Energy and Buildings*, Volume 37, Issue 1, pp. 77-86.

Pasanen, P., Hahkala, H., Holopainen, R. & Hyttinen, M. 2013, Quality of ventilation systems in residential buildings: Status and perspectives in Finland, *Securing the quality of ventilation systems in residential buildings: Existing approaches in various countries, Edited proceedings of the AIVC-TightVent International Workshop*, eds. A. Janssens, F.R. Carrié & F. Durier, INIVE, Brussels, 18-19 March, pp. 89.

Patton, M.Q. 1990, *Qualitative evaluation and research methods.* SAGE Publications, inc, Thousand Oaks, CA.

Pitts, A. (2017). Passive house and low energy buildings: Barriers and opportunities for future development within UK practice. *Sustainability*, *9*(2), 272.

Rohdin, P., Molin, A., & Moshfegh, B. (2014). Experiences from nine passive houses in Sweden–Indoor thermal environment and energy use. *Building and Environment*, *71*, 176-185.

Schmitt Y., Dal Savio S., Sparber W., PaMo. 2007. Monitoring of a multi familly Passive House in South Tyrol, Italy. *11th Intern.l Passive House Conference*, Bregenz - Austria, April 2007.

Steemers, K. & Manchanda, S. 2010, Energy efficient design and occupant well-being: Case studies in the UK and India, *Building and Environment,* vol. 45, no. 2, pp. 270-278.

Sundell, J., Levin, H., Nazaroff, W.W., Cain, W.S., Fisk, W.J., Grimsrud, D.T., Gyntelberg, F., Li, Y., Persily, A.K., Pickering, A.C., Samet, J.M., Spengler, J.D., Taylor, S.T. & Weschler, C.J. 2011, Ventilation rates and health: multidisciplinary review of the scientific literature, *Indoor air,* vol. 21, no. 3, pp. 191-204.

Takaro, T.K.; Krieger, J.; Song, L.; Sharify, D.; Beaudet, N. 2011. The Breath-Easy Home: The impact of asthma-friendly home construction on clinical outcomes and trigger exposure. Am. J. Public Health, pp. 55–62.

Ucci, M., Ridley, I., Pretlove, S., Mumovic, D., Davies, M., Oreszczyn, O., McCarthy, M. & Singh, J. 2004, Ventilation rates and moisture-related allergens in UK dwellings, *Proceedings of the 2nd WHO International Housing and Health Symposium. Vilnius, Lithuania,* pp. 328.

U.S. Department of Energy: Whole-House Ventilation. Available online: https://energy.gov/energysaver/ whole-house-ventilation. Accessed: 22 June 2018.

Van den Bossche, P., Caillou, S., Janssens, A. & Laverge, J. 2013, Quality of ventilation systems in residential buildings- Status and perspectives in Belgium, *Securing the quality of ventilation systems in residential buildings, Existing approaches in various countries, International workshop,* eds. A. Janssens, F.R. Carrié & F. Durier, AIVC, TightVent and INIVE, Brussels, 18-19th March, pp. 59.

Wang, Z., Bai, Z., Yu, H., Zhang, J. & Zhu, T. 2004, Regulatory standards related to building energy conservation and indoor-air-quality during rapid urbanization in China, *Energy and Buildings,* vol. 36, no. 12, pp. 1299-1308.

Wallner, P., Tappler, P., Munoz, U., Damberger, B., Wanka, A., Kundi, M., & Hutter, H. P. (2017). Health and wellbeing of occupants in highly energy efficient buildings: a field study. *International journal of environmental research and public health*, *14*(3), 314.

Wargocki, P. 2013, The effect of ventilation in homes on health, *International journal of ventilation,* vol. 12, pp. 101-118.

WHO 2010, *WHO guidelines for indoor air quality: selected pollutants,* Regional Office for Europe, Copenhagen, Denmark.

________2009, *WHO Guidelines for Indoor Air Quality, Dampness and Mould,* WHO Regional Office for Europe, Copenhagen, Denmark.

________1989, *Indoor air quality: organic pollutants, EURO Reports and Studies, No.111*, World Health Organisation Regional Office for Europe, Copenhagen.

________WHO 2006, *Air quality guidelines: global update 2005: particulate matter, ozone, nitrogen dioxide, and sulfur dioxide,* Regional Office for Europe, Copenhagen, Denmark.

________2000, *Air quality guidelines for Europe*, 2nd edn, Regional Office for Europe, Copenhagen.

APPENDIX A: Passive House post occupancy survey

The purpose of this questionnaire is to examine the perception of occupants on Passive house's indoor environmental (air, thermal) quality and its effects on the health and well-being of occupants. It is for research purposes only.
This will be done anonymously and answers will be kept completely confidential.

The study is being conducted by Masters Student, Samuel Babatola, at the Central European University, Budapest, under the supervision of Professor Diana Ürge-Vorsatz.

Your participation is an essential part of this research study and we hope that you will participate.

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1. To your knowledge, was your home designed and/or constructed to be any of the following? (check all that apply).

- ☐ Passive House
- ☐ Net-Zero Energy Home
- ☐ Green certified home
- ☐ EnergyPlus building
- ☐ none of the above
- ☐ I don't know

2. How many years have you been living in your dwelling? Indicate in years

The next few questions address features of your previous house

Description (optional)

3. In what type of building design did you previously lived in before moving into your current dwelling? (Single family home, duplex, apartment etc.)

- ◯ Single family home (detached)
- ◯ Small multi-unit building (duplex, row house etc. up to 4 units)
- ◯ Apartment or other (more than 4 units)

Other:

Short-answer text

4. How satisfied were you with the indoor air quality in your previous house?

- Extremely satisfied (1)
- Moderately satisfied (2)
- Slightly satisfied (3)
- Neither satisfied nor dissatisfied (4)
- Slightly dissatisfied (5)
- Moderately dissatisfied (6)
- Extremely dissatisfied (7)

5. Does anyone in your household including you have asthma, headache, sleeping problem or any other respiratory symptoms from allergies?

- Yes
- No

6. If yes to question 5, please select any health symptoms you or any member of your household have had in your previous house and how often

	Daily/almost daily	Weekly	Monthly/less frequently
General symptoms (headac...	☐	☐	☐
Upper respiratory tract symp...	☐	☐	☐
Lower respiratory tract sym...	☐	☐	☐
Eye symptoms (itching, dryn...	☐	☐	☐
Joint pain or swelling	☐	☐	☐
Muscle pain	☐	☐	☐
Sleeping problems	☐	☐	☐

Which of the symptoms get better when not at home?

Short-answer text

7. Briefly describe your health condition in your previous house: e.g, very good (1), good (2), moderate (3), bad (4) or very bad (5)

Long-answer text

The next few questions address features of your current dwelling (Passive House)

Description (optional)

8. Was your Passive house certified by Passive House Institute or by any other recognized body?

- ◯ Yes
- ◯ No

9. Is your Passive house adequately maintained, e.g. cleaning?

- ◯ Yes
- ◯ No

10. What are the temperature conditions like in your current dwelling? You may choose more than one option

	Too hot (1)	Suitably warm (2)	Suitably cold (3)	Too cold (4)
In Summer	◯	◯	◯	◯
In Winter	◯	◯	◯	◯

11. Are you satisfied with the ventilation system in your dwelling?

Long-answer text

11. Are you satisfied with the ventilation system in your dwelling?

Long-answer text

12. Are there unpleasant odors present in your present dwelling or in the immediate surroundings and what are they associated with? You may choose more than one option.

	No noticeable odor	Noticeable inside	Noticeable elsewhere...	Noticeable outside b...
Food odor	☐	☐	☐	☐
Cigarette smoke	☐	☐	☐	☐
Mold odor	☐	☐	☐	☐
Construction materials	☐	☐	☐	☐
General stuffiness	☐	☐	☐	☐
Smoke odor	☐	☐	☐	☐
Odor from traffic	☐	☐	☐	☐

13. Does anyone smoke indoors in your dwelling?

- Never
- Daily/almost daily
- Occasionally

14. As compared to your previous house, how satisfied are you with the indoor air quality in your present dwelling?

- Extremely satisfied (1)
- Moderately satisfied (2)
- Slightly satisfied (3)
- Neither satisfied nor dissatisfied (4)
- Slightly dissatisfied (5)
- Moderately dissatisfied (6)
- Extremely dissatisfied (7)

15. Does anyone in your household including you have asthma, headache, sleeping problem or any other respiratory symptoms from allergies??

- Yes
- No

16. If yes to question 15, please select any health symptoms you or any member of your household have had and how often after you start living in your present dwelling (Passive House)

	Daily/almo...	Weekly	Monthly or...	Never	Appear aft...	Reduced/c...	Increase a...	Not relate...
General sy...	☐	☐	☐	☐	☐	☐	☐	☐
Upper resp...	☐	☐	☐	☐	☐	☐	☐	☐
Lower resp...	☐	☐	☐	☐	☐	☐	☐	☐
Eye sympt...	☐	☐	☐	☐	☐	☐	☐	☐
Rash or ski...	☐	☐	☐	☐	☐	☐	☐	☐
Joint pain ...	☐	☐	☐	☐	☐	☐	☐	☐
Muscle pain	☐	☐	☐	☐	☐	☐	☐	☐
Sleeping p...	☐	☐	☐	☐	☐	☐	☐	☐

17. Briefly describe your state of health in your present dwelling as compared to while living in your previous house: e.g, very good (1), good (2), moderate (3), bad (4) or very bad (5)

Long-answer text

18. Can you offer any other comments or observations that may be helpful in determining the environmental condition of your passive house?

Long-answer text

19. Gender of respondent

- Male
- Female
- Prefer not to say

20. Age of respondent

Short-answer text

21. Do you smoke or have smoked in the past?

- No, I have never smoked
- No, I quit smoking with the past 12 months
- No, I quit smoking more than 12 months ago
- Yes, I smoke currently

22. Including yourself, how many people live permanently in your dwelling? (Indicate the number of occupants by age group.)

- [ ] Adult (aged between 18 and 65)
- [ ] Children aged 7 to 17
- [ ] Children (under the age of 7)

23. My building is located in:

- ○ Central Europe (Germany)
- ○ UK and Ireland
- ○ North America (USA, Canada)
- ○ Eastern Europe
- ○ Australasia/ South Pacific
- ○ Korea, Japan and China

Other:

Short-answer text

APPENDIX B: Statistical analysis

TEST OF HYPOHYPOTHESES

HYPOTHESIS 1

H_0: Passive house does not improve the health of occupants

vs.

H_1: Passive house improves the health of occupants, at **α=0.5%**

ANALYSIS OF HYPOTHESIS 1

TABLE 1.1: Model summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.153[a]	.023	.003	1.625

The model summary table above provides the **R**, **R^2**, adjusted **R^2** and the standard error of the estimate. The **R** column represent the value of **R**, the multiple correlation coefficient. **R** measured the quality of the prediction of the dependent variable, in this case, responses of those who lived in Passive house. The value **0.153** indicates a poor level of prediction. The **R square** column represents the **R^2=0.023** (also called the coefficient of determination), is the proportion of variance in the dependent variable that can be explained by the independent variables (technically, it is the proportion of variation accounted for by the regression model above and beyond the mean model). Also, it can be seen from the value of **0.153** that the independent variables explain **15.3%** of the variability of the dependent variable. It can also be seen from the table above that the values of the **Adjusted R Square** and the **standard error** are **0.003** and **1.625** respectively.

TABL 1.2: ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	5.975	2	2.988	1.132	.327[a]
	Residual	250.800	95	2.640		
	Total	256.776	97			

The F-ratio in the ANOVA table (see above) tests whether the overall regression model is a good fit for the data. The table shows that the independent variables statistically significantly predict the dependent variable, **$F(2, 95) = 2.640$, $p=0.327< 0.5$** (i.e., the regression model is a good fit of the data)

TABLE 1.3: Table of coefficients and significance

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
1 (Constant)	2.812	.788		3.569	.001	1.248	4.377
How satisfied were you with the indoor air quality in your previous house	.129	.086	.153	1.504	.136	-.041	.298
Briefly describe health condition in your previous house	.002	.163	.001	.010	.992	-.322	.325

Unstandardized coefficients indicate how much the dependent variable varies with an independent variable when other independent variable is held constant.

Decision rule: If **$p < 0.05$**, then **H_0** is not rejected, otherwise, **H_0** is rejected.

Conclusion: Since **$p>0.05$** (from the **Sig.** column in the **table 1.3** above (the values of **p** are **0.136** and **0.992** respectively for the two independent variables), we have the statistical reason (using multiple regression analysis in **SPSS**) to reject **H_0**. We therefore conclude that **Passive house improves the health of occupants**.

HYPOTHESIS 2

H_0: The prevalence of health symptoms is more frequent in Passive house than in Non-Passive house

vs.

H_1: The prevalence of health symptoms is more frequent in Non-Passive house than in Passive house, at **$\alpha=0.5\%$**

ANALYSIS OF HYPOTHESIS 2

TABLE 2.1: Model summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.228[a]	.052	.011	1.143

The model summary table above provides the **R**, **R^2**, adjusted **R^2** and the standard error of the estimate. The **R** column represent the value of **R**, the multiple correlation coefficient. **R** measured the quality of the prediction of the dependent variable, in this case, responses of those who lived in Passive house. The value **0.228** indicates a fair level of prediction. The **R square** column represents the **R^2=0.052** (also called the coefficient of determination), is the proportion of variance in the dependent variable that can be explained by the independent variables. (Technically, it is the proportion of variation accounted for by the regression model above and beyond the mean model). It can be seen from the value of **0.153** that the independent variables explain **22.8%** of the variability of the dependent variable. It can also be seen from the table above that the values of the **Adjusted R Square** and the **standard error** are **0.011** and **1.143** respectively.

TABL 2.2: ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	6.636	4	1.659	1.269	.288[a]
	Residual	121.568	93	1.307		
	Total	128.204	97			

The F-ratio in the ANOVA table above tests whether the overall regression model is a good fit for the data. The table shows that the independent variables statistically significantly predict the dependent variable, **F (4, 93) = 1.307, p=0.288< 0.5** (i.e., the regression model is a good fit of the data)

TABLE 2.3: Table of coefficients and significance

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
1 (Constant)	6.290	.700		8.985	.000	4.900	7.680
Your household have had in your previous house and how often? (General symptoms and allergies)	-.187	.149	-.128	-1.256	.212	-.482	.108
Your household have had in your previous house and how often? (Upper respiratory tract symptoms)	-.201	.149	-.137	-1.351	.180	-.497	.094
Your household have had in your previous house and how often? (Lower respiratory tract symptoms)	-.034	.149	-.024	-.230	.818	-.331	.262
Your household have had in your previous house and how often? (Eye symptoms)	.181	.143	.128	1.266	.209	-.103	.464

Unstandardized coefficients indicate how much the dependent variable varies with an independent variable when all other independent variable is held constant.

Decision rule: If **$p < 0.05$**, then **H_0** is not rejected, otherwise, **H_0** is rejected.

Conclusion: Since **$p>0.05$** (from the **Sig.** column in the **table 2.3** above, the values of **p** are **0.212, 0.180, 0.818** and **0.209** respectively for the two independent variables), we have the statistical reason (using multiple regression analysis in **SPSS**) to reject H_0. We therefore conclude that **the prevalence of health symptoms is more frequent in Non-Passive house than in Passive house**.

APPENDIX C: Pictures of Passive House dwellings in Munich, Germany

Passive House Certified Dwelling

Passive House (Back facade)

Passive House dwelling (Front facade)

Passive House (Rear facade)

Passive House (Front facade)